

Bachelor's thesis

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***Studies on Atmospheric Neutrino Flux Modelling with
KM3NeT/ARCA***

Abstract

There are several models for the modelling of atmospheric neutrino flux used for the analysis of data from the neutrino detector KM3NeT/ARCA. Previously, the model MCEq was implemented for these studies. Another, data-driven, model is DAEMONFLUX. This thesis focuses on implementing and testing this new model, as well as comparing it to MCEq:

ARCA21 atmospheric neutrino flux was analysed using MCEq, and DAEMONFLUX, by evaluating MC data using flux histograms, likelihood scans fixing certain parameters and inspecting the individual model flux components. Additionally, a model confusion check was done to see what happens when analysis is done when injecting with one model but fitting with the other. Finally, both models were checked against real KM3NeT data. All this allowed for a comparison of the two models and showed that their results are very similar, indicating that DAEMONFLUX works and can be applied for future analysis.

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1 Introduction

Trying to understand and observe obvious objects in the sky, like the sun and the moon, for most of human history, made astronomy the first natural science to gain a high level of sophistication, going back as far as at least 2000 BCE [1]. These observations were done based on visible light up until the 1930s when radio astronomy was first proposed [2].

Nowadays, in addition to photons, other particles like neutrinos serve as astrophysical messengers, helping humanity to further explore and understand the cosmos.

The advantage of neutrino astronomy is that neutrinos are not deflected by magnetic fields and rarely absorbed on their path through space, making them ideal candidates for messenger particles [3].

One possibility of detecting these neutrinos is with Cherenkov detectors of large volume [4], such as the Cubic Kilometre Neutrino Telescope (KM3NeT) in the Mediterranean Sea. In such detectors, it is important to consider neutrinos resulting from the interactions of cosmic rays in the atmosphere, referred to as atmospheric neutrinos. In order to model atmospheric neutrino flux, several approaches were developed to be able to analyse detector events as accurately as possible.

One of these models is MCEq, a model that has previously already been implemented and used for flux evaluation. A newer model, DATA-drivEN MuON-calibrated atmospheric Neutrino Flux (DAEMONFLUX), could now also be applied to atmospheric neutrino flux analysis with KM3NeT.

The objective of this thesis is to implement DAEMONFLUX and then compare it to the results from MCEq.

This is done by first reproducing MCEq analysis results with Monte Carlo (MC) data such as flux histograms and likelihood scans of certain parameters and then also applying DAEMONFLUX to these approaches. Furthermore, a model confusion check is executed, testing how results change when one of the two models is used for injecting, but the other for fitting and vice versa. Lastly, the two models are checked against real data from KM3NeT/ARCA21 to further compare their performance.

In this thesis, Chapter 2 provides the physical background necessary to these studies and explains the detection principle of KM3NeT. Chapter 3 then explains the mathematical and statistical concepts behind the models, while Chapter 4 shows how the DAEMONFLUX model was actually implemented. Finally, Chapter 5 provides the results of the analysis and comparison between the two models, with Chapter 6 concluding the thesis by summarising these results.

2 Neutrino Physics

In order to understand the studies done in this thesis, it is important to first familiarise oneself with the fundamental physical background, especially with the relevant neutrino detector, KM3NeT, as well as neutrino physics itself.

2.1 Neutrinos

First proposed in 1930 by Pauli, as an explanation for the angular momentum and energy in β -decay, and first observed in 1956 [3], the neutrino is an elementary particle, specifically a fermion due to its spin of $\frac{1}{2}$. There are three different neutrino flavours, ν_e , ν_μ , and ν_τ , each associated by charged current weak interaction with a corresponding charged lepton e^- , μ^- and τ^- [5], [6].

In the standard model of particles, neutrinos are considered to have a charge and mass of zero. However, in recent years, experiments have proven that the mass is in fact small but non-zero [6]. The Karlsruhe Tritium Neutrino Experiment (KATRIN) determined an upper mass limit of $0.45 \frac{\text{eV}}{c^2}$ in 2025 [7].

What makes neutrinos so important for astrophysics is that they only interact via the weak interaction, by either exchanging a $W^\pm$ or Z^0 boson [6]. This means they are essentially not absorbed or deflected by magnetic fields while travelling through the universe. Therefore, neutrinos can reach Earth unscathed, with their tracks pointing directly to their source and thus possibly providing information on the origin of cosmic rays [3].

2.2 Cosmic Rays

Cosmic rays are high-energy ionized nuclei, mostly protons, but also alpha particles and heavier nuclei. They hit the Earth's atmosphere at a rate of $\sim 1000 \text{ m}^{-2} \text{ s}^{-1}$ and their energies can be as high as 10^{20} eV . Nearly all low energy cosmic rays originate from outside the solar system but from within the Galaxy, while high-energy cosmic rays source candidates are extragalactic, such as AGN or SGBs, although their precise origins, as well as the reason for their acceleration to high energies, are not fully known yet [8], [9].

The differential spectrum of cosmic rays follows a power-law $\frac{d\Phi}{dE} \propto E^{-\gamma}$, where γ is the spectral index. γ changes at characteristic energies [10].

The most common approach to explain cosmic ray acceleration is the Fermi mechanism. In this mechanism, individual charged particles are accelerated through the transfer of macroscopic kinetic energy of moving magnetized plasma onto them. By repeatedly crossing the shock front resulting from the plasma, the energy per particle is significantly increased [8]. Candidates in which this acceleration can take place are for example AGN, Gamma Ray Bursts (GRBs) or Pulsar Wind Nebulae (PWNe) [11].

The accelerated charged particles, e.g. protons, then collide with the photon background or material in dense environments, such as other protons, resulting in interactions like

$$p + \gamma \rightarrow \pi + N + X \quad (1)$$

where N represents a nucleon and X another product [8].

The pions can then decay, resulting in neutrinos [8]:

$$\pi^\pm \rightarrow \mu^\pm + \nu_\mu^{(\mp)} \quad (2)$$

The resulting muons can also decay [8]:

$$\mu^\pm \rightarrow e^\pm + \bar{\nu}_e^{(-)} + \nu_\mu^{(-)} \quad (3)$$

Additionally, the decay of kaons is also a neutrino origin [8]:

$$K^\pm \rightarrow \mu^\pm + \bar{\nu}_\mu^{(-)} \quad (4)$$

Since neutrinos only interact weakly, they can escape this dense environment and help answer the questions of cosmic ray origins and accelerations when detected on Earth. The previously mentioned primary cosmic rays produce secondary atmospheric cosmic rays when interacting in the atmosphere, resulting in hadrons and their decay products. These secondary cosmic rays peak in the GeV range but extend to higher energies following a power-law spectrum [12].

2.3 Atmospheric Neutrino Fluxes

Atmospheric neutrino fluxes primarily result from the decay of charged mesons arising from cosmic-ray showers [13].

Furthermore, atmospheric secondary cosmic ray showers also cause decay products like muons, that also need to be considered in the flux [14].

High-energy atmospheric neutrino fluxes can be divided into conventional (conv) atmospheric neutrino flux and prompt atmospheric neutrino flux [15].

2.3.1 Conventional Atmospheric Neutrino Flux

Conventional atmospheric neutrino flux is a result of the decay of pions (Equation 2) and kaons (Equation 4) as well as the muons produced from their decay (Equation 3). Since the lifetimes of these particles are so long, at higher energies, it is likely that they interact before they decay [15].

Due to these interactions before decay, the flux Φ approximately follows the primary cosmic ray spectrum, but typically one power steeper, with $\frac{d\Phi}{dE} \propto E^{-3.7}$ and dominates for atmospheric neutrinos with energies up to 300 TeV [16], [17].

Conventional atmospheric neutrino flux has an angular dependency because the decay probability is impacted by the atmospheric depth the parent particles traverse in the atmosphere [18].

2.3.2 Prompt Atmospheric Neutrino Flux

Prompt atmospheric neutrino flux refers to the neutrinos resulting from the decay of charmed heavy short-lived mesons, like D^0 or $D^\pm$ [19]. The name prompt is derived from the promptly decay of these mesons due to their short lifetimes [13]. Because of these prompt decays, the mesons cannot re-interact in the atmosphere before decay. This results in the prompt component having no angular dependence [20] and a flux of $\frac{d\Phi}{dE} \propto E^{-2.7}$, inheriting the spectral index of the cosmic ray flux directly [16].

For energies above 100 TeV, the prompt atmospheric neutrino flux starts to dominate the total spectrum [17].

Due to poor coverage by collider experiments, predicted prompt flux can vary greatly. Until now, prompt atmospheric neutrino flux has not yet been measured [19].

2.4 The Cubic Kilometre Neutrino Telescope (KM3NeT)

This section introduces the functionality and concept of KM3NeT, the neutrino telescope relevant to this thesis.

2.4.1 Neutrino Telescopes

Since neutrinos only interact via the weak force, telescopes of large volume are required for their detection in statistically significant numbers [3].

KM3NeT is a neutrino telescope with several locations in the Mediterranean Sea, as depicted in Figure 1. Other telescopes are, for example, the Radio Neutrino Observatory Greenland (RNO-G) or the IceCube Neutrino Observatory at the South Pole.



Figure 1: Locations of the Cubic Kilometre Neutrino Telescope (KM3NeT) in the Mediterranean Sea, taken from *KM3NeT* [21]

2.4.2 Detection Principle

Neutrino detection can for example be achieved by using Cherenkov radiation [22].

The Cherenkov effect is a phenomenon that occurs when a charged particle travels through a medium with refractive index n with a velocity v higher than the speed of light $\frac{c}{n}$ in that medium. Then an electromagnetic radiation, called Cherenkov radiation, is emitted because this charged particle causes polarisation in the atoms along its track, resulting in these atoms becoming dipoles. The time variation of these dipole fields then causes the radiation [23].

This only happens when $v > \frac{c}{n}$ because only then the dipoles are not symmetrically arranged. Therefore, only then the dipole moment is non-vanishing.

The angle between the trajectory of the charged particle and the Cherenkov radiation, in Figure 2 referred to as θ_c , can be determined using Equation 5, where $\beta = \frac{v}{c}$. For $\beta = \frac{1}{n}$, the radiation is emitted in the direction of the particle [23].

$$\cos(\theta_c) = \frac{1}{n\beta} \quad (5)$$

Since the determination of θ_c enables the calculation of the particle velocity, it is therefore also suitable to help with particle identification [23].

So, when a high-energy neutrino interacts with matter and a charged particle emerges

from that interaction, that particle will also have high energy. An example is the charged current interaction of muon neutrinos with nucleons [24]:

$$\nu_\mu + N \rightarrow \mu^- + X \quad (6)$$

If the resulting particle (in the example, this would be the muon or potentially X) then travels through a transparent medium at a speed higher than c_{medium} , as previously described, it disrupts the energy equilibrium of the atoms in its way. These atoms then regain equilibrium by the emission of photons, which result in a blueish glow, referred to as Cherenkov radiation, and can be detected. The Cherenkov effect is the optical counterpart to the sonic boom effect [25]. As in such a sonic boom, the radiation spreads in a cone-like shape [23], as depicted in Figure 2.

Detecting Cherenkov radiation is therefore a way to indirectly also detect neutrinos.

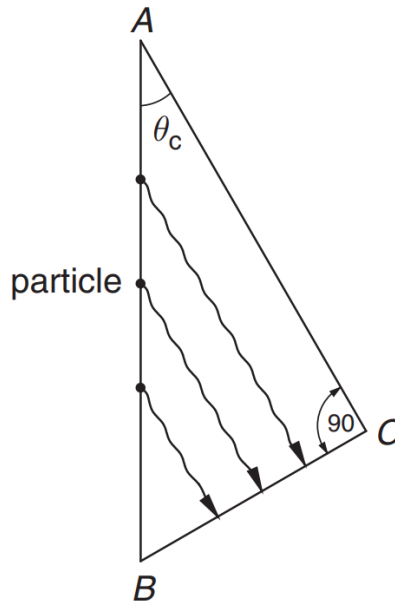


Figure 2: Depiction of the Cherenkov angle θ_c between the trajectory of a charged particle, moving from A to B and Cherenkov radiation spreading towards C, taken from Grupen and Shwartz [23]

Since a large volume of an optically transparent medium is required to measure the radiation, mediums like glacial ice, lake water or deep ocean water are commonly used [4].

2.4.3 Measurement Electronics

Photo Multiplier Tubes (PMTs) In these mediums, modules containing so-called Photo Multiplier Tubes (PMTs) are deployed, enabling the detection of the Cherenkov photons [26].

A Photo Multiplier Tube (PMT) functions in the following way:

When a photon enters the PMT, it excites the electrons in a photocathode to emit photoelectrons through the external photoelectric effect. These electrons are then

accelerated by a focusing electrode onto an electron multiplier, also called a dynode. On this dynode, the electrons are multiplied by secondary electron emission. This process is then repeated on several following dynodes, resulting in an exponential increase of electrons. In total, the dynodes in the PMT multiply the photoelectrons coming from the photocathode by magnitudes up to 10^6 to 10^7 . Finally, a collecting anode converts the electrons emitted from the last dynode into an electric pulse [27]. This pulse is proportional to the number of detected photons, which can then be used to estimate energy in reconstructed neutrino interactions [28].

A schematic depiction of a PMT can be seen in Figure 3.

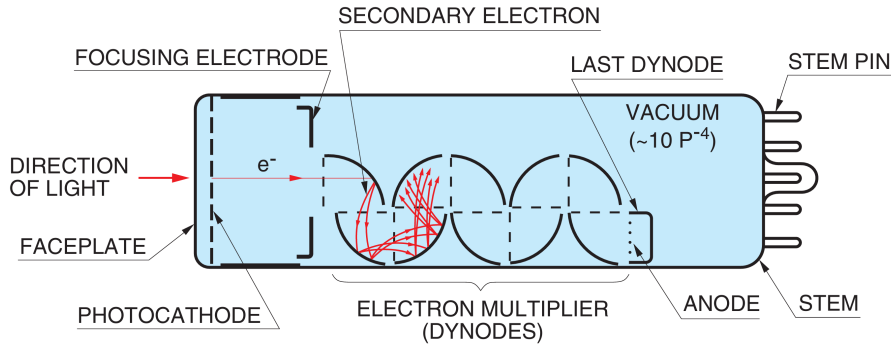


Figure 3: Construction of a Photo Multiplier Tube (PMT), showing the photocathode, focusing electrode, secondary electron emission on the dynodes and the anode, taken from Hamamatsu Photonics K.K. Editorial Committee [27]

Digital Optical Modules (DOMs) DOMs are the detector’s sensor models. Each consists of a glass sphere, specifically designed to withstand deep-sea pressure, housing multiple PMTs, as well as additional instruments for calibration of the measured signals and determination of the sensor’s geometrical position, like compasses and accelerometers. In KM3NeT, each DOM holds 31 small PMTs, to enable 360° detection [26].

Inside each DOM is an FPGA, a computer chip meant to decide within nanoseconds whether to measure incoming photons.

So when a neutrino causes Cherenkov radiation, these DOMs can detect the resulting photons, amplify and convert the signals to square waves and send them via optical fibres to the control station on shore, where the data is then analysed [26].

Using the time at which the photons were detected, the location of the responsible DOM, and the strength of its output signal, it is possible to reconstruct the path of the neutrino through the telescope as well as its energy [28]. For charged particles causing the radiation with a longer lifetime and longer tracks measured in the detector, the neutrino direction can therefore be reconstructed with a higher resolution [22].

A 3D-graphic of a KM3NeT DOM can be seen in Figure 4.

Detection Units (DUs) In KM3NeT, a DU consists of 18 DOMs, connected by an electro-optical cable and two additional ropes for stabilization. These ropes are connected to an anchor at the bottom to keep the DU attached to the seabed and to a

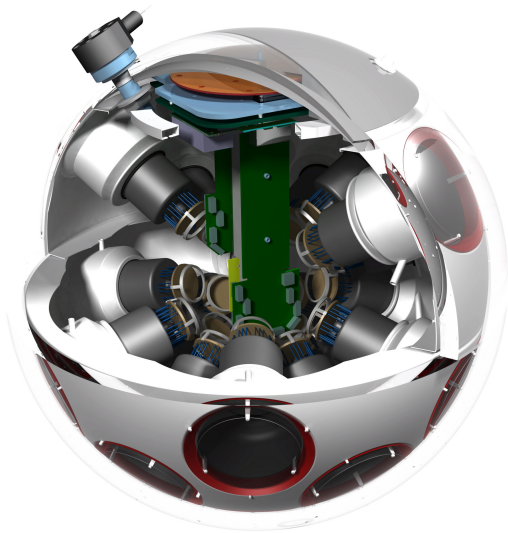


Figure 4: Schematic depiction of a DOM with a glass sphere, PMTs with electronic circuits at the back to provide high voltage, the FPGA and other sensors, taken from *KM3NeT - opens a new window on our universe* [26]

buoy at the surface to keep the DU vertical. Each DU is also coupled to a junction box for subsea power and data transmission [26].

2.4.4 Astroparticle Research with Cosmics in the Abyss (ARCA)

ARCA is one of the two current detectors in KM3NeT, located about 100 km off the coast of Sicily, Italy, as depicted in Figure 1. It is being deployed for the detection of high-energy cosmic neutrinos. Construction started in 2015 and is still ongoing [26]. Once ARCA is completed, it will, according to the current plan, consist of two detector blocks, containing 115 DUs each [29], resulting in a telescope with an instrumented volume of $\sim 1 \text{ km}^3$. At the present moment, it is operating with 51 DUs. The data used in this thesis is from ARCA21, meaning the ARCA detector with only 21 DUs [26]. In ARCA, these DUs are about 700 m high, anchored at a depth of about 3500 m. The DOMs have a vertical difference of about 40 m while the horizontal distance between the DUs is about 100 m.

ARCA enables the mapping of 87 % of the sky and detection of neutrinos between several tens of GeV and PeV [26].

A schematic depiction of the ARCA layout can be seen in Figure 5.

KM3NeT's other neutrino detector, Oscillation Research with Cosmics in the Abyss (ORCA), is located about 40 km off shore Toulon, France, also shown on Figure 1. Its denser built enables the detection of lower-energy neutrinos [26]. ORCA's layout is also depicted in Figure 5.

Since this thesis focuses on astroparticle physics and therefore high-energy neutrinos, only data from ARCA, more specifically ARCA21, is used.

KM3NeT/ARCA was running with 21 detector lines for 287.4 days [30], excluding

downtime and runs measuring data unsuitable for evaluation.

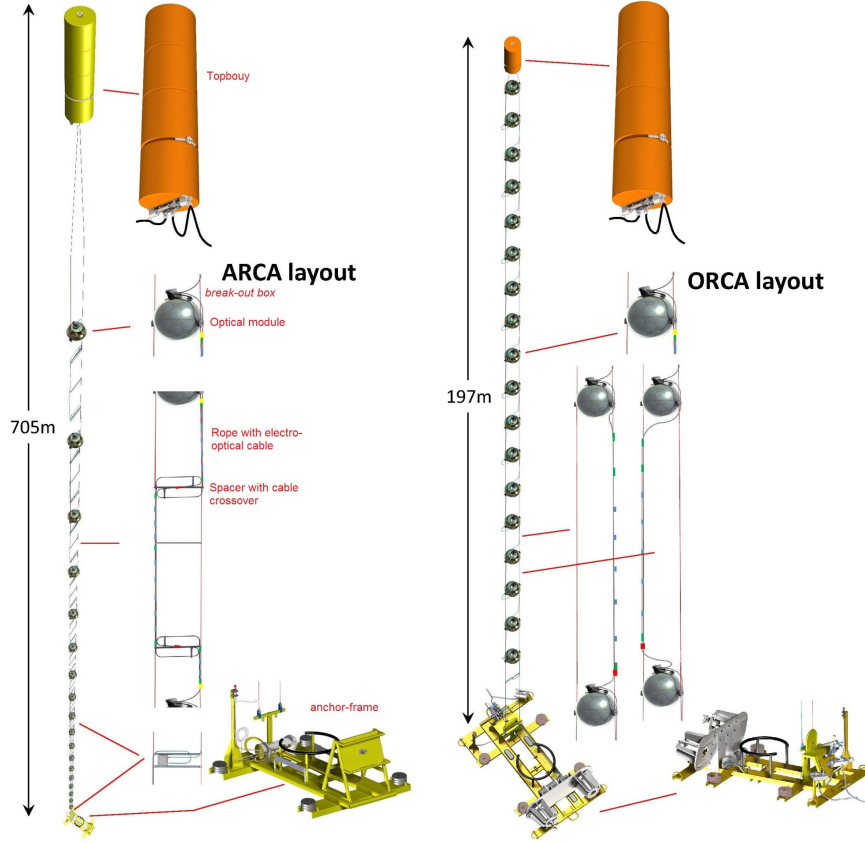


Figure 5: Schematic depiction of the layouts of ARCA (left) and the denser built of ORCA (right), each showing the top buoy and anchor frame at the bottom of the sea, with the DOMs on ropes in between, taken from *KM3NeT - opens a new window on our universe* [26]

2.4.5 Atmospheric Muon Background

When trying to detect neutrinos, it is also important to consider the impact that muons originating from secondary cosmic ray showers have, since they are also detected and need to be distinguished from the muons resulting from neutrinos. An approach to achieve this is to only use data from upward going muons, and thereby using Earth as an atmospheric muon absorbing shield. However, it is possible that downward going atmospheric muons are falsely reconstructed as upgoing tracks, which is why an atmospheric muon background still needs to be considered [14].

3 Analysis Methods

This chapter describes the statistical and mathematical concepts as well as code packages necessary to understand for the studies in this thesis.

3.1 Monte Carlo (MC) Simulations

A detector measurement cannot be directly evaluated without considering detector effects. These effects are so complex that simulations are required to be able to account for them. Therefore, MC simulations need to model expected events based on physical values. These MC events are created with a true energy that can be translated into a reconstructed energy using reconstruction algorithms, so that it is known how the simulated events would actually be detected by the neutrino telescope [31].

Each of these simulated events is generated with a base deviating from the physical spectrum, so a good statistical spectrum, mostly for high-energy events, can be provided. To regain a physical meaning, these events are then later re-weighted using a physical spectrum.

For KM3NeT/ARCA, particles are simulated along with their interactions, light production in water and PMT detection, resulting in datasets including simulated and reconstructed values [32].

3.2 Forward-Folding

The studies done with both main models used in this thesis, DAEMONFLUX and MCEq, is based on a data analysing method called Forward-folding.

Forward-folding refers to the idea of accounting for detector effects in model predictions to try to make these predictions more similar to what the detector actually measures [33].

On the contrary, the more traditional 'unfolding' approach would be to decipher the detector data after measuring, meaning, for example, trying to account for selection effects. This comes with the difficulties of biases being introduced that could lead one to consider effects that make the data seem to fit better to the expectation, without them actually being the source of why the detector measured certain values [33].

The accounting for detector effects in Forward-folding is done by comparing detector data to the model predictions by a likelihood function. These model predictions are calculated by re-weighting Monte Carlo (MC) simulated data [34], [35].

In order to achieve that, both the detector and the MC data are binned in the reconstructed variables, in this case, the energy and the zenith angle.

The binning results in histograms stating the amount of events per bin. For the real data histograms, this shall be referred to as d_j , for the MC histograms as μ_j . The latter is determined by model-specific weights, whose calculation calculation is dependent on the flux parameters θ of the used model, evaluated at the true, simulated quantities of each event.

The bin expectation μ of a flux component k for every bin j can be calculated using Equation 7, where w_i^j refers to the flux weights of an event i in bin j [36].

$$\mu_j^k(\theta) = \sum_i w_i^j \quad (7)$$

The total bin expectation μ_j of bin j is then equal to the sum of the individual bin expectations of each flux contribution [37].

μ_j and d_j can then be compared via a likelihood function [36], [38]:

$$\mathcal{L}(\mu_j(\theta)) = \prod_j \mathcal{L}_{\text{bin}}^j(\mu_j(\theta); d_j) \quad (8)$$

Then the flux parameters θ can be varied to maximise this function and the whole process is repeated until best-fit values are found. A Poisson likelihood is used for the fit.

3.3 Poisson Likelihood

Since the number of events is presumed to follow a Poissonian distribution, a Poisson likelihood is used. This likelihood is given by Equation 9 for one bin [36].

$$\mathcal{L}(\theta | d) = \frac{\mu(\theta)^d \cdot e^{-\mu(\theta)}}{d!} \quad (9)$$

The negative logarithm of this likelihood, relevant for the determination of the best-fit values in the maximum likelihood method, is

$$-\log(\mathcal{L}(\theta | d)) = -d \cdot \log(\mu(\theta)) + \mu(\theta) + \log(d!). \quad (10)$$

This log likelihood is used because it takes the form of a sum rather than a product and is therefore easier to work with [39]. To allow for implementation into numeric optimisers that minimise, the negative function is used, which results in the same outcome as maximising the positive equivalent.

3.4 Maximum Likelihood Method

In the Forward-folding method, the best-fit values for the parameters are settled by minimising $-\log(\mathcal{L}(\mu_j(\theta); d_j))$.

To determine the confidence intervals of these best-fit parameters, a profile likelihood scan is executed, meaning a set of fit parameters α is varied on a fixed grid while for the other parameters, the log-likelihood (Equation 10) is minimised.

Equation 11 describes the ratio of the likelihood with all fit parameters being free and some (α) being fixed. It is referred to as the test statistic and can give a confidence interval, which is giving the confidence level of containing α [40].

$$\text{TS} = -2 \cdot \log \left(\frac{\mathcal{L}(\theta, \alpha | d)}{\mathcal{L}(\theta | d)} \right) = -2 \cdot \Delta \log(\mathcal{L}) \quad (11)$$

3.5 Asimov Dataset

An artificial dataset, called the Asimov dataset, is used to check the sensitivity of the analysis by fixing true parameter values for θ and computing the event numbers per bin, from which data histograms can be made [40], [35].

When performing a free fit with all parameters, the injected values are recovered [40].

3.6 Flux Models

The computation of neutrino fluxes comes with many possible uncertainty sources such as a lack of information on the cause of atmospheric particle showers and difficulties in accurately modelling in the phase space relevant to neutrino observations [41].

Therefore, models were developed that are meant to minimise these uncertainties.

In this thesis, several different models for atmospheric neutrino flux are used and compared. This section shall explain their functionality, specifically their parameters used in the Forward-folding method.

3.6.1 Astrophysical Flux

The diffuse astrophysical neutrino flux is modelled as a single power law and assumed to be isotropic [42], as shown in Equation 12, where γ is the spectral index, Φ the flux normalization, E_ν the primary neutrino energy and $E_{\text{ref}} = 100$ TeV a reference energy for unit independency [37], [43].

$$\Phi_{\text{astro}}(E_\nu) = (\Phi_0^{\text{astro}} \cdot 10^{-18} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}) \times \left(\frac{E_\nu}{E_{\text{ref}}} \right)^{-\gamma_{\text{astro}}} \quad (12)$$

3.6.2 Matrix Cascade Equations (MCEq)

MCEq is a model working by solving cascade equations for atmospheric particle cascades and constructing splines containing a hadronic interaction as well as a primary cosmic ray flux model. These splines originate from pre-computed MCEq simulations for each model, so they can be interpolated and do not need to be recalculated each run. The built splines both use the same interaction model (Sibyll2.3c), but different cosmic ray flux models: One utilizes the Gaisser-H4a and the other the GSF model [35].

These models can be interpolated via an interpolation factor λ_{int} [37]:

$$\lambda_{\text{int}} w_{\text{H4a}} + (1 - \lambda_{\text{int}}) w_{\text{GSF}} \quad (13)$$

This is done so they can be evaluated more quickly via a likelihood fit.

To be able to consider cosmic ray energy spectrum uncertainties, another factor is added along with flux normalization factors [37], as can be seen in Equation 14, where a normalisation factor Φ_0^{conv} and a cosmic ray spectral index shift $\Delta\gamma_{\text{CR}}$ are additionally introduced.

$$\Phi_{\text{conv}}(E_\nu) = \Phi_0^{\text{conv}} \times (\lambda_{\text{int}} w_{\text{H4a}} + (1 - \lambda_{\text{int}}) w_{\text{GSF}}) \times \left(\frac{E_\nu}{E_{\text{ref}}} \right)^{-\Delta\gamma_{\text{CR}}} \quad (14)$$

The MCEq code is available on GitHub [44].

3.6.3 DAte-drivEn MuOn-calibrated atmospheric Neutrino Flux (DAEMONFLUX)

One possibility to minimise the uncertainties in neutrino flux computation is to implement the correlation between cosmic muons and atmospheric neutrinos into the model. The advantage of this is that these muons emerge from the same processes as

the neutrinos, the decay of charged mesons, but are much easier to detect [41]. One approach of accounting for this correlation between muons and neutrinos is Data-drivEn MuOn-calibrated atmospheric Neutrino Flux (DAEMONFLUX). Other than similar attempts of implementing this, DAEMONFLUX also includes flux and muon charge ratio measurements to account for further cosmic ray uncertainties and calibrate the fluxes. This resulted in a model including a covariance matrix with uncertainties, DAEMONFLUX [41].

In DAEMONFLUX, MCEq is used to solve one-dimensional coupled cascade equations to evaluate lepton fluxes. The Data-Driven hadronic interaction Model (DDM) serves as a model for lepton flux calculations using particle cross section measurements from fixed target accelerators. It includes hadron cross sections for $\pi^\pm$, $K^\pm$, p and n parametrized from fixed target data of different energies [41].

Additionally, the Global Spline Fit (GSF) model acts as the cosmic ray flux measurements by linking direct space and indirect air shower array observations and interpolating between datasets. In DAEMONFLUX, GSF was reduced to only six parameters using Principal Component Analysis (PCA), a method for simplifying datasets, since other parameters were irrelevant to the desired analysis [41].

Using error propagation, the amount of free calibration parameters could be reduced to the amount of independent cross sections. In order to increase flexibility at higher energies, additional parameters were introduced by extrapolation.

Table 1 gives an overview of the parameters resulting from the different models.

Astrophysical parameters	MCEq parameters	DAEMONFLUX DDM parameters	DAEMONFLUX GSF parameters	Muon background
astro_norm astro_index	atmo_norm delta_gamma ($\Delta\gamma_{\text{CR}}$) lambda_int (λ_{int})	$K_{158\text{G}}^+$ $K_{2\text{P}}^+$ $K_{31\text{G}}^+$ $K_{158\text{G}}^-$ $K_{2\text{P}}^-$ $K_{31\text{G}}^-$	GSF ₁ GSF ₂ GSF ₃ GSF ₄ GSF ₅ GSF ₆	muon_norm
		n _{158G} n _{2P}		
		p _{158G} p _{2P}		
		$\pi_{158\text{G}}^+$ $\pi_{20\text{T}}^+$ $\pi_{2\text{P}}^+$ $\pi_{31\text{G}}^+$ $\pi_{158\text{G}}^-$ $\pi_{20\text{T}}^-$ $\pi_{2\text{P}}^-$ $\pi_{31\text{G}}^-$		

Table 1: Overview of the names of all used parameters, listed by model [41]

The names of these 18 DDM parameters include a base name and an index. This base

name refers to the type of hadron, either $\pi^\pm$, $K^\pm$, p or n. The indices of the parameters indicate the beam energy of the respective fixed target experiment. The number gives the value of the energy while the letter refers to the first letter of the energy unit. So, e.g. p_{158G} stands for the proton production yield resulting from a fixed-target collision with an incoming beam energy of 158 GeV [41].

This combination of MCEq with GSF and DDM, along with uncertainty propagation, resulted in DAEMONFLUX being one of the flux models with the lowest uncertainties in comparison to other methods so far, making it a great contender as a replacement for other models.

The code for DAEMONFLUX can be found on GitHub [45].

3.6.4 Gaisser

Another flux model was developed based on research by Thomas Gaisser, therefore referred to as Gaisser in this thesis.

Gaisser proposed a model in 1990 to account for the production of muons from the decay of kaons and pions. He originally ignored the curvature of the atmosphere, therefore overestimating the attenuation of through-going muons [46].

A model accounting for the curvature of the earth can be implemented into MCEq using the GaisserZenithFactor as described in Equation 15, where $R_{K/\pi}$ is the kaon-pion-ratio [38], θ is the muon zenith angle and ϵ_π and ϵ_K are the critical energies of pion and kaon [46].

$$B(E, \theta) = \frac{1}{1 + a_\pi \cdot E \cos \theta / \epsilon_\pi} + R_{K/\pi} \cdot \frac{1}{1 + b_K \cdot E \cos \theta / \epsilon_K} \quad (15)$$

The muon flux can then be modeled, using another normalisation parameter A , as in Equation 16 [47].

$$\frac{d\Phi_\mu}{dE d\Omega} = AE^{-\gamma} B(E, \theta) \quad (16)$$

3.7 pyForwardFolding (pyFF)

The entire analysis was executed using the open-source framework pyForwardFolding (pyFF) [38], which uses the JAX package [48] as a back end.

It is a modernised version of NewNuMuFit (NNMFit), a framework originally developed for IceCube data analysis [35].

To implement a model in pyFF, a config file needs to be created that defines the used models, factors, components and their parameters (including their injected values and priors) as well as the binning size for histograms, the lifetime and the path to the used data.

4 DAEMONFLUX Implementation

In the config file for MCEq, astro, atmo, and prompt components are implemented. In order to add DAEMONFLUX as a component with all its parameters, the following steps were necessary.

4.1 DAEMONFLUX Weights

To calculate the weights needed for the implementation of DAEMONFLUX, an input of the used location, energy, zenith, and flux type is required. The location was set to 'generic' for all calculations. Since the used data includes events caused by all neutrino flavours as well as their antiparticles, a mask was implemented to ensure the correct flux type was used to calculate the weights for each flavour. Since in the conventional flux, hardly any tau (anti) neutrinos are expected and the prediction for prompt flux in DAEMONFLUX is done using MCEq, the mask sets the weights of the events caused by these neutrinos to zero. To correctly calculate and implement the DAEMONFLUX weights, the following challenges needed to be overcome:

4.1.1 Up/down Symmetry

The generic location used for ARCA in this thesis is limited to downgoing neutrino flux for DAEMONFLUX. Since upgoing events should not be excluded from this analysis, the assumption of up/down symmetry was made, suggesting that the flux could be mirrored at the horizon and still result in the same conclusions.

This assumption is supported by the geometric argument that downgoing neutrinos entering earth at a zenith angle of α produce the same effect as upgoing neutrinos entering on the opposite side of the earth at an angle of $\beta = \pi - \alpha$. The reason for this is that cosmic ray flux is assumed to be isotropic and that these neutrinos traverse the same slant depth of atmosphere due to the approximate sphericity of the earth [43], [49]. Therefore, the flux calculations, with θ being the zenith angle, are only dependent on $|\cos(\theta)|$ [50], since $|\cos(\alpha)| = |\cos(\pi - \alpha)|$.

In case the symmetry assumption does not impact the results of the analysis decisively, the zenith angle of the upgoing events could therefore be mirrored at the horizon to downgoing angles. Then these angles could also be implemented in the DAEMONFLUX studies.

To test whether this assumption is true and whether the angles can be mirrored without meaningful changes to the analysis results, it was tested using MCEq, which allows both downgoing and upgoing neutrino flux and is therefore suitable for testing the symmetry assumption.

In order to get the mirrored angles θ_{mirrored} , the following Equation 17 was used, where θ refers to the previous, unmirrored angles:

$$\theta_{\text{mirrored}} = \arccos(|\cos(\theta)|). \quad (17)$$

Using MCEq, a 2D scan was performed, and the flux components were analysed. This was done with weights calculated using the up/down symmetry assumption and weights calculated without the assumption. When comparing these values in the 2D scan, one obtains the plot in Figure 6. The concept of 2D scans is further described in subsubsection 5.2.2.

Here, 'with uds' refers to the values calculated with the assumption and 'without uds'

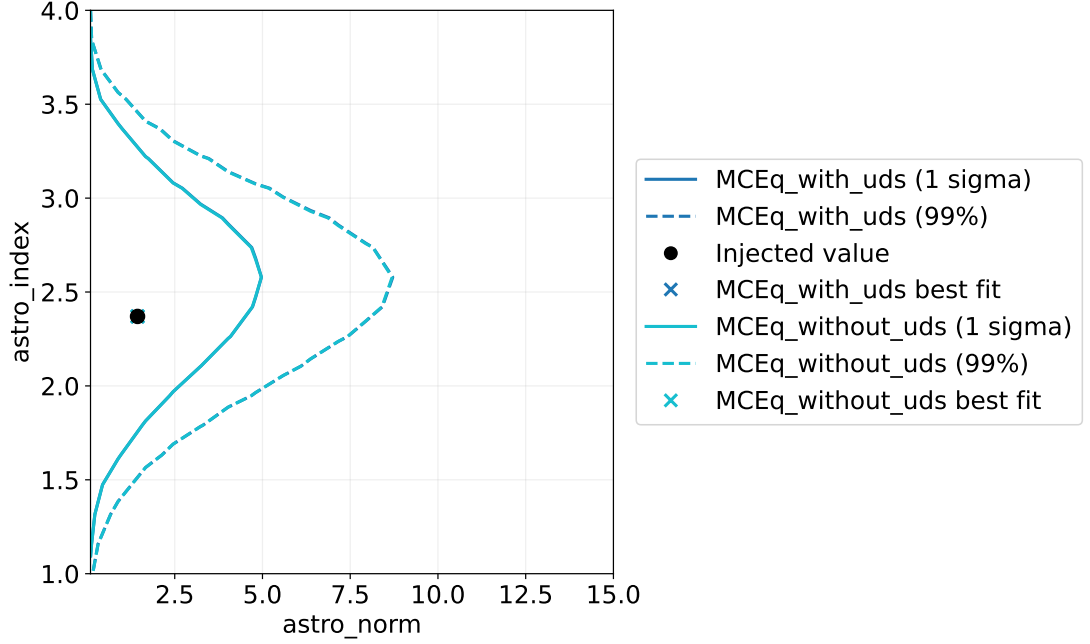


Figure 6: 2D comparison scan using weights calculated with and without the up/down symmetry (uds) assumption

to those calculated without. The plot shows overlapping curves, indicating that the results are very similar.

Additionally, plots evaluating the separate components of the data, resulting from the calculations with and without the assumptions, were created. As the curves are also overlapping in these individual flux component histogram plots, the relative difference in the expected events was determined for each of them, resulting in Figure 7.

Figure 7 shows non-zero differences for the atmo and prompt components. Since these

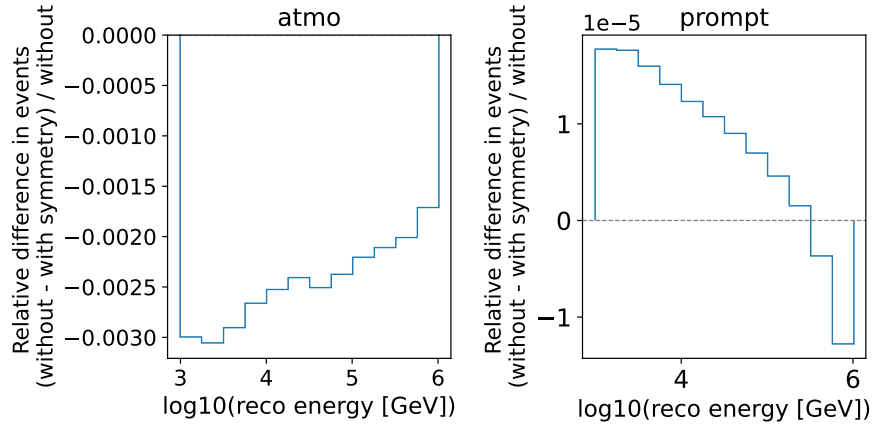


Figure 7: Relative difference of events calculated without and with the symmetry assumption in plots evaluating per component, for the atmo and prompt components

differences are in magnitudes of 10^{-3} and 10^{-5} , they are small enough to be considered insignificant to the analysis results.

Therefore, the up/down symmetry assumption can be considered true. This means that for the analysis with DAEMONFLUX at the generic location, the upgoing zenith angles can be mirrored so that they can be implemented as downgoing flux.

For the astro and muon components, the difference is constantly at 0.0, meaning the input data with(out) the up/down symmetry assumption was the same. This matches the expectation since both of these components are not dependent on the zenith angle and therefore don't change with the mirroring.

4.1.2 Small Weight Cut-Off

Because the resulting non-zero DAEMONFLUX weights of the events caused by electron anti neutrinos were of magnitudes as small as 10^{-324} and it was necessary to divide by these figures in the reweighting process of the GradientReweight, as explained in subsection 4.4, python was not able to carry out this calculation, resulting in NaN values.

The electron anti neutrino weights can be seen in Figure 8a, while all other weights are

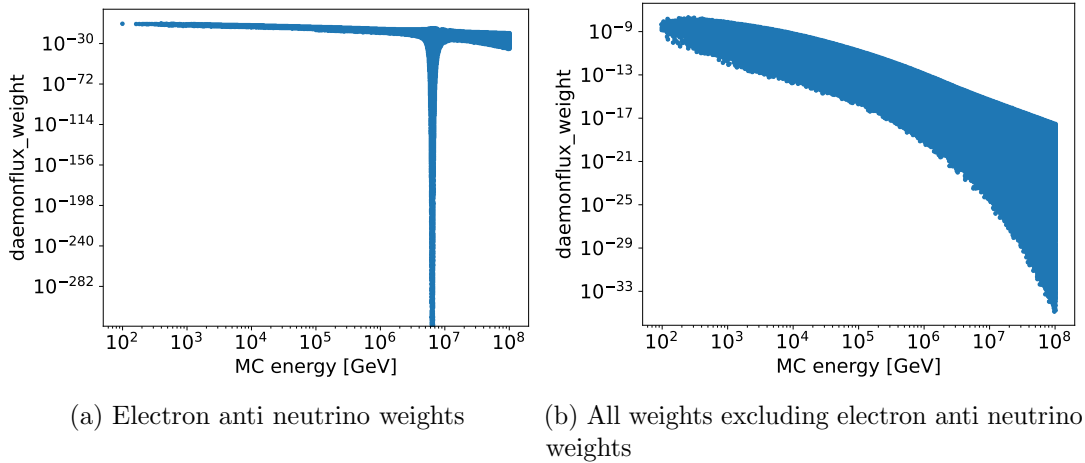


Figure 8: Plots depicting selected weights, based on particle type

depicted in Figure 8b.

These weights of the electron anti neutrinos extend to such small magnitudes as they are more likely to be absorbed by the earth due to the Glashow resonance [51], which occurs when an electron anti neutrino strikes an electron, creating a W^- boson. This predominantly happens at an energy of 6.3 PeV [52], matching the energy range in which the weights are so small, see Figure 8a.

To overcome this issue, events with weights smaller than 10^{-36} were excluded, as the weights in Figure 8b are all bigger than this cut-off value, so no weights of any other flavours were excluded. This resulted in the weights that can be seen in Figure 9.

This cut-off does not impact the analysis results significantly since they only sum up to an event number of the magnitude 10^{-27} over 300 days.

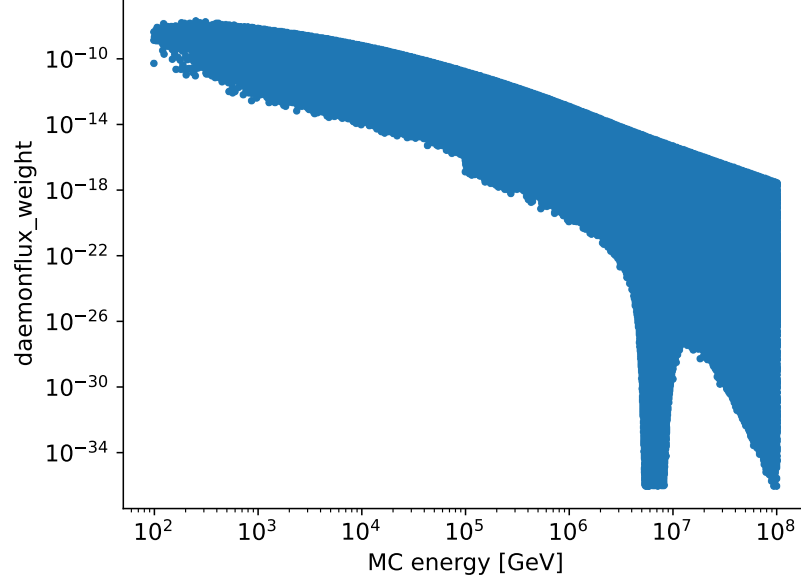


Figure 9: Remaining weights after cutting off those smaller than 10^{-36}

4.2 DAEMONFLUX Parameter Priors

To be able to constrain the DAEMONFLUX parameters to prevent unphysical results by encoding prior knowledge, priors were implemented. In general, uniform priors were set on all the parameters that are to be fit to ensure results with a physical meaning. That means that an assumption about the parameter values is made by injecting a starting value, the prior seed, as well as prior bounds that limit the interval in which each parameter can be fitted. These hard limits are known as uniform priors and set to $[-\infty, \infty]$ for all DAEMONFLUX parameters. Their seeds are all set to 0.0, which means they are not deviated because this value is implemented in units of the parameter's standard deviation. Generally, the parameters are built so that their base value is defined as 0.0 with a standard deviation of 1σ .

4.2.1 Gaussian Priors

For the 24 DAEMONFLUX parameters, additional Gaussian priors were implemented. This is to suppress high fit values. Gaussian prior refers to the assumption of the parameters being distributed normally around a mean with a certain variance [53]. They lead to the effect that the further away a parameter value is being fit from the injected mean, the higher the prior term becomes. As it is the fitting goal to minimise the total loss, which includes this prior term, the fit values are therefore pushed towards the mean.

In Equation 18, the data term is depicted in green while the prior term is blue. Here, μ_i and d_i are the expected and observed counts per bin respectively, with $\mathcal{P}$ being the Poisson log likelihood. In the prior term, P_i is the fitted parameter value, O_i the

injected mean and σ_i the estimated error [41], [43].

$$\text{LLH} = \sum_{\text{bin}} \mathcal{P}(\mu_i, d_i) + \left(\frac{P_i - O_i}{\sigma_i} \right)^2 \quad (18)$$

The chosen priors each have a mean of 0.0 and a standard deviation of 1.0 for the DAEMONFLUX parameters, as well as Gaussian seeds that are again set to 0.0, meaning they are unshifted.

4.2.2 Covariance

Due to the correlation of the 24 parameters, independent Gaussian priors would not suffice in correctly describing their uncertainties, so a covariance matrix needed to be implemented in a prior multivariate section. This additional prior section also contributes to the total loss, but this time one term for all 24 parameters instead of one term each. The diagonal entries of the matrix are the variances of each parameter, while the off-diagonal ones refer to the parameter covariances.

The correlations are used to reduce the penalties that are summed up in the total loss term. For example, if one parameter is pulled up during the fit and another was also pulled up, a strong positive correlation between those parameters would result in a smaller penalty than without the implementation of the matrix. On the other hand, if one parameter was pulled up and the other down, their correlation would increase the penalty term.

This penalty can be described by Equation 19, where n correlated parameters are the components of a vector X , and V describes the covariance matrix [54], while ΔL is the scalar penalty value.

$$\Delta L = X^T V^{-1} X \quad (19)$$

Again, these priors were implemented with seeds and bounds, respectively set to 0.0 or $[-\infty, \infty]$.

This matrix could be extracted from the DAEMONFLUX code, see reference [45].

A plot of the parameter correlation can be seen in Figure 10.

4.3 Implementation of Prompt Flux

The prompt flux firstly was implemented using `atmo_norm` as the norm for prompt for MCEq. In order to check whether this would also make sense for the DAEMONFLUX implementation, several 1D likelihood scans were performed, comparing the results with different norms. 1D likelihood scans are described in further detail in subsubsection 5.2.1. The assumption that the norm for the prompt component could be tied to the `atmo_norm` is made since both conventional and prompt fluxes share the same primary flux description [55] in the MCEq calculation in DAEMONFLUX. Examples of these scans with different prompt component norms can be seen in Figure 11.

The DAEMONFLUX scans show a slightly wider result for a config in which the norm for prompt is tied to the `atmo_norm`, depicted in blue in Figure 11. The orange curve shows the scan resulting from a config in which the norm of prompt is not tied to the `atmo_norm` but instead to an entirely separate parameter, unrelated to the `astro_norm`. It was implemented because the results for MCEq and DAEMONFLUX originate from different codes. Because of this reason and the narrower outline, this parameter was

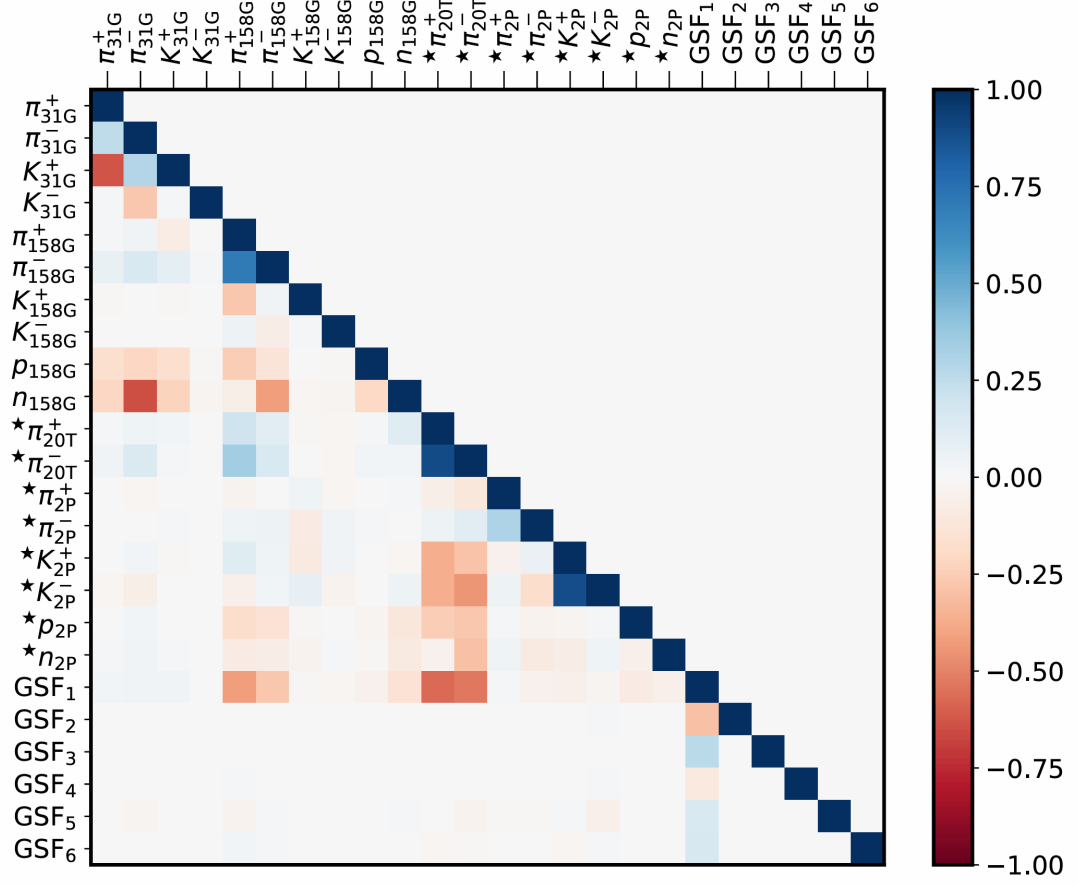


Figure 10: Correlation between the 24 DAEMONFLUX parameters, taken from Yañez and Fedynitch [41]

then chosen as the norm of prompt for all configs. It shall be referred to as `prompt_norm` in the following.

For consistency reasons, and so that the two models could be compared easily, the code for `prompt_norm` was then also applied to the MCEq config. In both of the models, this code includes a Gaussian prior for this parameter, that was implemented because it constrains the parameter and narrows the scan results more than without the prior, as can be seen in Figure 12. Leaving `prompt_norm` unrestricted could result in unphysical values, while ignoring existing theoretical knowledge, especially since the prompt flux is not calibrated using DAEMONFLUX, because surface muons are not sensitive to prompt fluxes [45].

Following data from the IceCube Neutrino Observatory [37], a half Gaussian with 90% of its mass under 3 was chosen for this prior, resulting in a standard deviation of approximately 1.82 with a mean of 0.00.

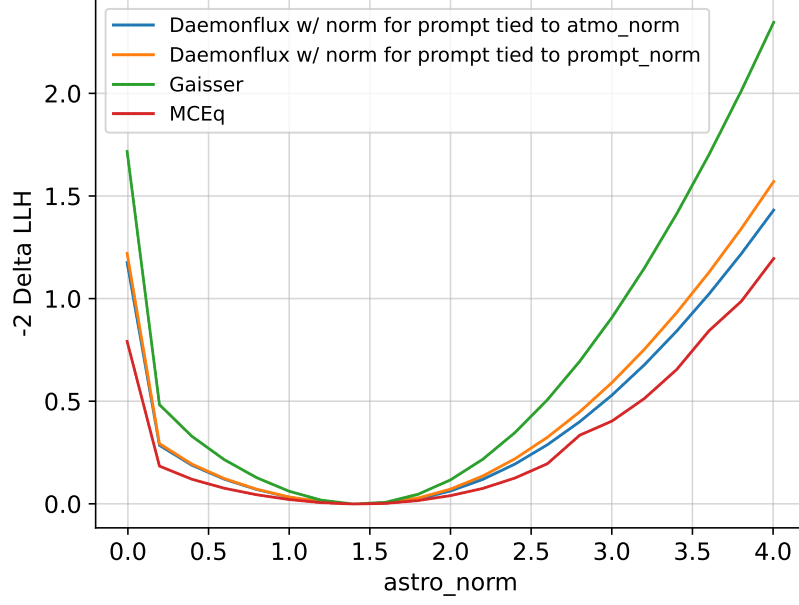


Figure 11: Astro norm likelihood scan comparison with different DAEMONFLUX prompt norms (one tied to the atmo_norm and one to prompt_norm), MCEq and Gaisser

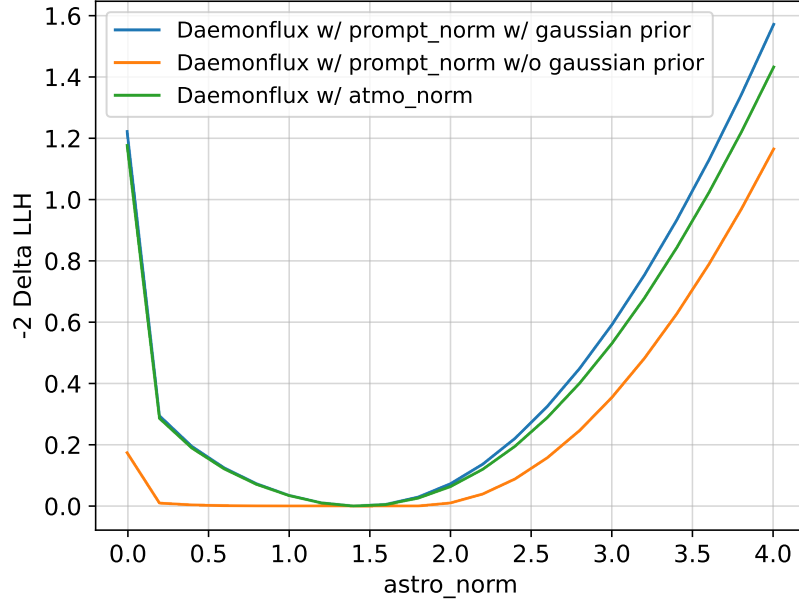


Figure 12: Astro norm likelihood scan comparison of DAEMONFLUX scans with and without a Gaussian prior for prompt_norm, as well as a scan where the prompt norm is again tied to atmo_norm

4.4 Gradients

Since the 24 DAEMONFLUX parameters do not all change by the same amount when varied, it was necessary to implement a GradientReweight factor, R , for all of them. This factor can be modeled as in Equation 20 [38], where $w_{i,0}$ is the baseline weight, g_i the pre-calculated parameter gradient, $\theta_{k,0}$ the parameter base value, θ_k the parameter value, i meaning of the i -th event and k the k -th parameter.

$$R_i = \frac{w_{i,0} + \sum_k (\theta_{k,0} - \theta_k) g_{i,k}}{w_{i,0}} \quad (20)$$

In order to achieve this, all parameters were varied by several units of their standard deviation. When plotting the calculated flux over the (deviated) value of the parameter, a linear graph can be seen in all 24 cases. Examples of these plots can be seen in Figure 13. All plots can be found in Appendix A.

Since all graphs follow a linear trajectory, the slope of this trajectory was determined

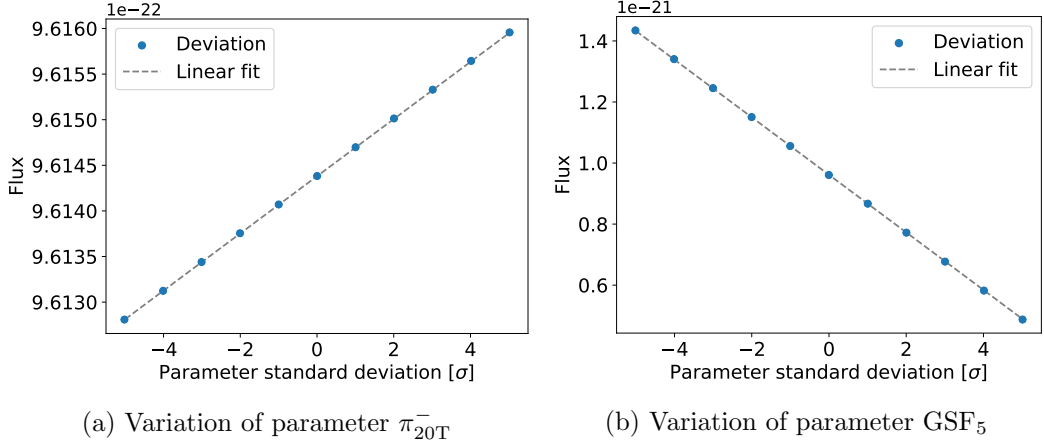


Figure 13: Example plots for the gradient determination of two parameters, each showing the linear trajectory of the calculated flux resulting from varying the respective parameter by units of its standard deviation

for each parameter and each event, and then implemented in the GradientReweight factor.

5 Results

After the complete implementation of DAEMONFLUX, the model was applied to the following, always along with MCEq, to be able to compare the results originating from the two models.

5.1 Histograms

Firstly, histograms were plotted using the calculated DAEMONFLUX weights in order to compare them to the atmospheric weights of MCEq. One histogram using the energy as the x-axis and one using the zenith angle. In these plots in Figure 14, two MCEq curves are shown each. This is because two types of weights were calculated for MCEq using two different models, GSF and Gaisser-H4a.

It can be seen that their results are both very similar to the DAEMONFLUX curve,

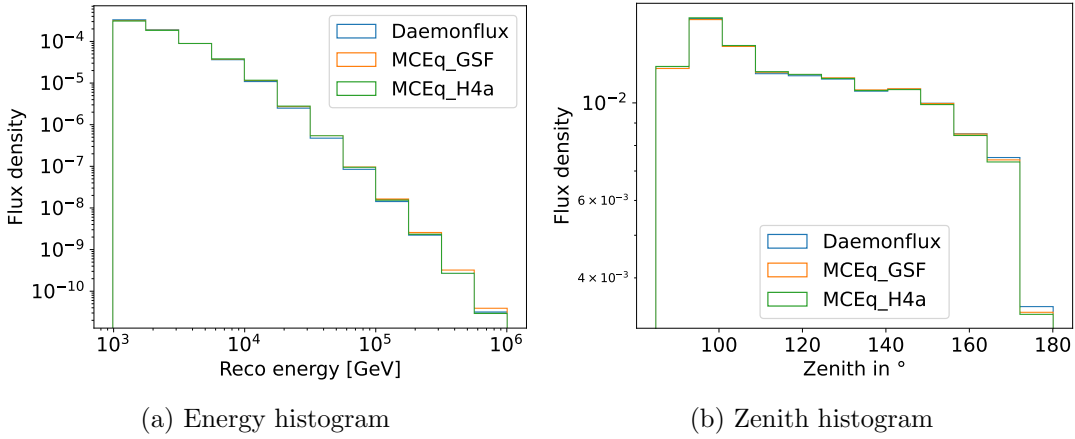


Figure 14: Histograms comparing DAEMONFLUX with the two MCEq models

which is why the relative differences between either MCEq model and this DAEMONFLUX curve were additionally plotted, as can be seen in Figure 15. These differences are relatively close to zero, further showing that the MCEq and DAEMONFLUX results are very similar.

Furthermore, a plot showing the expected flux for all components in DAEMONFLUX separately was created. It can be seen in Figure 16.

This Figure 16 shows that the prompt and astro components follow a similar curve. For energies up to a magnitude of 10^5 GeV, the DAEMONFLUX component dominates. For higher energies, the dominating component is astro.

5.2 Likelihood Scans

To determine the maximum likelihood value of one or two signal parameters, in this case of the astro_norm, astro_index and atmo_norm with fits, these parameters were fixed and only the remaining parameters fitted, resulting in the scans discussed in the following sections. The injected value of astro_norm was always 1.44, while 2.37 was injected for astro_index and 1.0 for atmo_norm, based on IceCube best fit values.

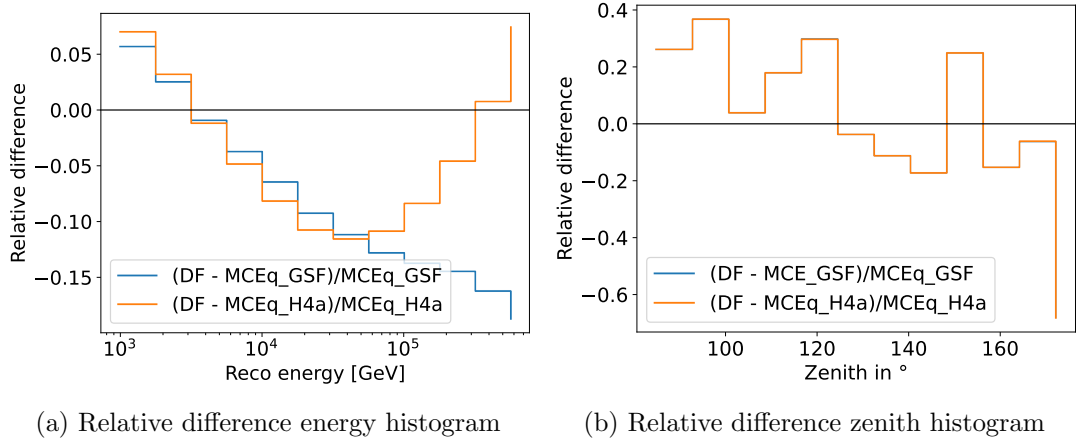


Figure 15: Relative differences of the DAEMONFLUX (DF) and the MCEq results, one curve for each MCEq model. In the zenith histogram plot (b), only one curve is visible due to the curves entirely overlapping.

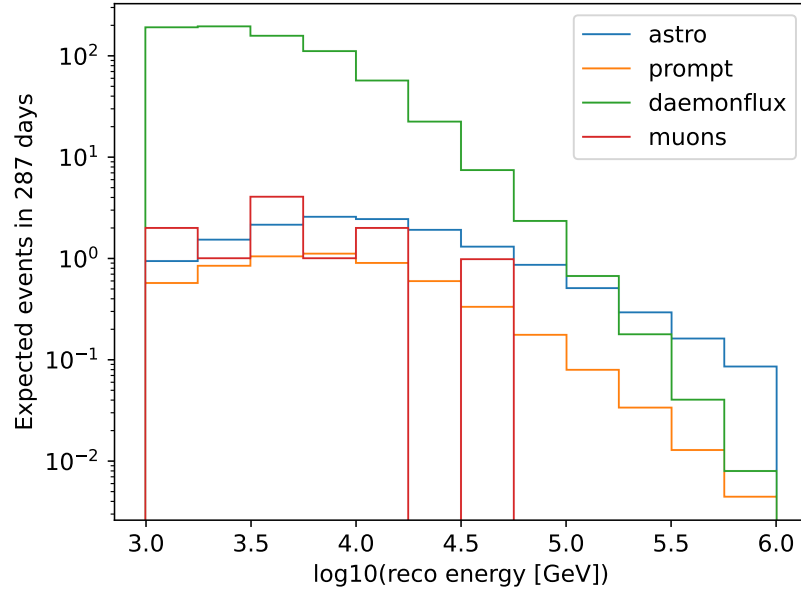


Figure 16: Plot showing the evaluation per component for the DAEMONFLUX components

5.2.1 1D Scans

1D refers to the fixing of one parameter only.

1D scans using the different models described in subsection 3.6 can be found in Figure 17a.

The plot shows that the scan is narrower for DAEMONFLUX than for MCEq, while Gaisser is the narrowest. A narrower scan implies that the parameters are more constrained, giving a smaller uncertainty, as the likelihood decreases faster when moving away from the best-fit value and therefore deteriorates quicker.

That Gaisser has the narrowest scan is due to the model having fewer parameters and

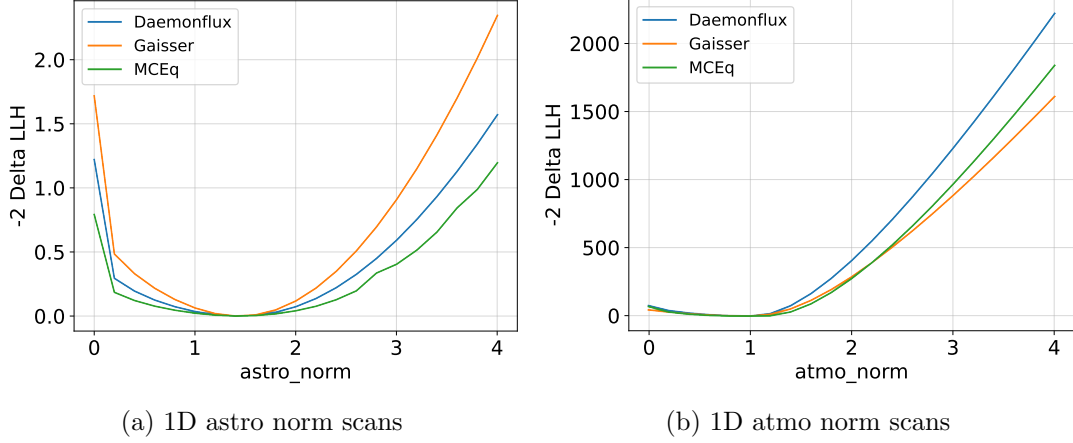


Figure 17: 1D likelihood scan comparisons using the models DAEMONFLUX, Gaisser and MCEq

the fit results therefore not being able to adapt to injected deviations as easily. On the other hand, the DAEMONFLUX scan is wider and the MCEq one the widest. This is because both models have more parameters than Gaisser, making them more adaptable, allowing the fit to compensate for deviations and therefore making the scans wider. Because DAEMONFLUX is based on correlations between its parameters that were implemented as priors, effectively reducing its flexibility, its scan is narrower than the MCEq scan.

The wideness of a scan therefore cannot give indications about which model is better, but only about what impact each model has on the fit outcomes.

In Figure 17a, the minima of the scans are all at approximately 1.44, matching the injected `astro_norm` value. This is a direct consequence of the Asimov method, which recovers the injected values when fitting.

Additionally, scans were also done scanning the `atmo_norm`, resulting in Figure 17b. Again, the minima and therefore the best-fit values match the injected one.

5.2.2 2D Scans

A 2D scan can be performed when fixing two parameters. Scans with fixed `astro_norms` and `astro_indices` can be seen in Figure 18 using DAEMONFLUX and MCEq separately. The 2D scan plots all show the best-fit values via a red cross and the injected values via an orange circle. Additionally, 1σ , 2σ and 99% confidence regions around the best fit are depicted.

A singular plot comparing the results of both models can be seen in Figure 19. It shows that these results, using DAEMONFLUX and MCEq, are again quite similar with DAEMONFLUX being more constrained, as described in subsubsection 5.2.1. For both models, the determined best-fit values match with the injected ones.

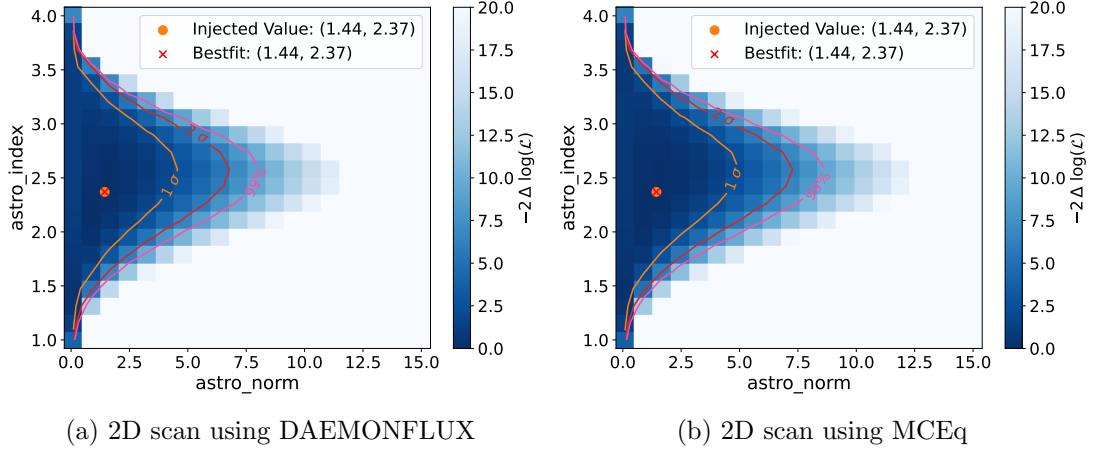


Figure 18: 2D scans fixing the `astro_norm` as well as the `astro_index`, showing the bestfit as well as the injected values

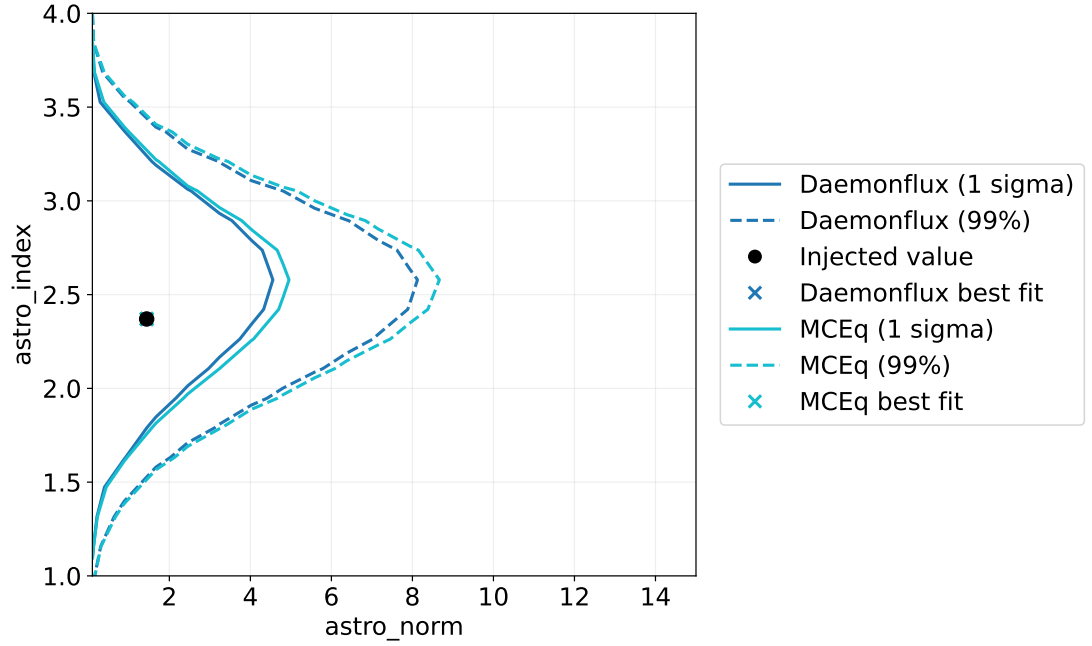


Figure 19: 2D scans fixing the `astro_norm` and the `astro_index`, comparing the results of the MCEq and the DAEMONFLUX model

5.3 Model Confusion Check

Previously, the injected and fitted flux models were always the same. This section discusses the results of injecting and fitting different flux models.

To achieve this, 1D likelihood scans were performed for all cases listed in Table 2.

injected \ fitted	DAEMONFLUX	MCEq
	Case A	Case B
DAEMONFLUX	Case A	Case B
MCEq	Case C	Case D

Table 2: Cases used in the model confusion check

These scans can be seen in Figure 20.

In addition to the scans, the discovery sensitivity was determined for each case for the

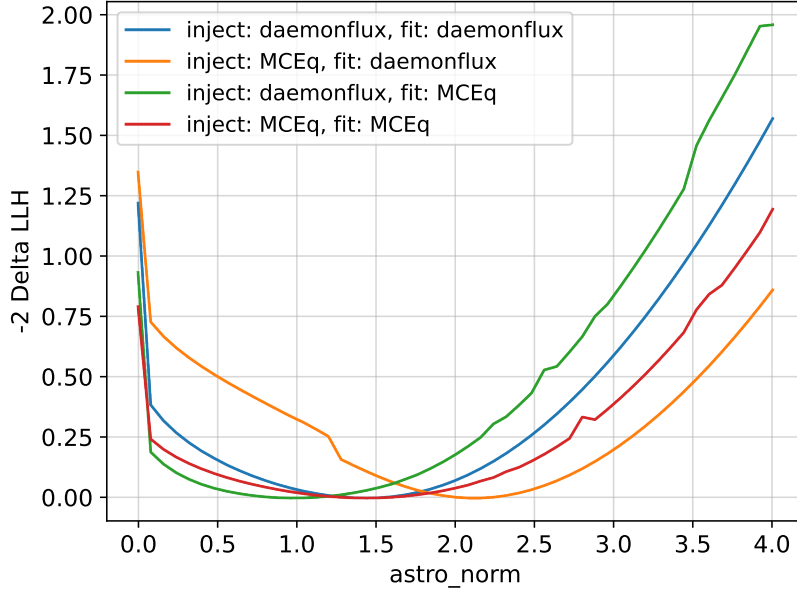


Figure 20: 1D scans for all model confusion check cases listed in Table 2

astro_norm scan in units of the standard deviation sigma. This refers to the square root of the value of the likelihood where the astro_norm is zero in Figure 20, meaning the value at which no astro flux can be excluded. The different discovery sensitivities for all cases are listed in Table 3.

injected \ fitted	DAEMONFLUX	MCEq
	1.10	0.97
DAEMONFLUX	1.10	0.97
MCEq	1.16	0.89

Table 3: Discovery sensitivity in units of σ of the cases used in the model confusion check

These results show that the discovery sensitivities for all cases are relatively close to one. Additionally, one can observe that the discovery sensitivity is higher when DAEMONFLUX is fitted and lower when MCEq is fitted, which matches the result, previously discussed for the 1D-scans, that DAEMONFLUX generally produces narrower scans than MCEq.

Furthermore, the biases of these scans were also determined, meaning the difference in units of the `astro_norm` between the minima of the scans and the injected value (1.44). In this case, the bias is defined as best-fit value – injected value. This shift of some scans due to the biases can also be seen in Figure 20.

For a scan where the input and fit model are the same, in this case, cases A and D, a bias of zero is expected when using the Asimov dataset, since parameters are recovered from data that came from the same model. When using different models, the parameters differ, resulting in the fitting model making assumptions that could deviate from the injected values.

The determined biases can be found in Table 4.

injected \ fitted	DAEMONFLUX	MCEq
	DAEMONFLUX	MCEq
DAEMONFLUX	0.00	−0.48
MCEq	0.72	0.00

Table 4: Biases of the cases used in the model confusion check

As expected, the biases for cases A and D are 0.0 while they are not for cases B and C. In case B, the bias has a negative value of −0.48, meaning the fit underestimated the `astro_norm`. On the other hand, it was overestimated in case C, with a positive bias value of around 0.72. It is important to note that these biases are smaller than the fit resolution, meaning that in an actual fit, they would not necessarily be resolvable from zero.

Due to this bias and overestimation in case C, further investigation into which parameter caused this deviation was reasonable. A plot showing the best fit deviation from the nominal for each DAEMONFLUX parameter as well as the `prompt_norm`, using MCEq as the inject model and DAEMONFLUX as the fit model, is depicted in Figure 21a.

It can be seen that `prompt_norm` as well as the parameters K_{2P}^+ and K_{2P}^- deviate the most.

By calculating the flux for a fixed angle (in this case, 60°) and only setting one of the 24 DAEMONFLUX parameters to a certain value (here it was varied by units of its own standard deviation, between -1.0σ and 1.0σ), the plots in Figure 22 could be created.

They each show the relative difference of the fluxes calculated with the varied parameter to the flux calculated with the unvaried parameter (0.0σ) for each variation of one of the parameters K_{2P}^+ and K_{2P}^- . That means that when these curves differ from zero, the parameter value is changing and therefore has an influence on the resulting flux values. For these two parameters specifically, they take effect over almost the entire energy range, although more at higher energies. Since this is the range in which the results are sensitive to the `astro_flux`, this could be the reason their best fit deviation in Figure 21a differs that much from 0.0.

Other parameters that also take effect for most of the energy range are, for example, n_{2P} or p_{2P} . For these, the best fit deviation from the nominal is also more significant than for the remaining parameters. The parameter variation plots for all other DAEMONFLUX parameters can be found in Appendix B.

Figure 21a also shows that the parameters are quite constrained since their best fit deviation from the nominal is so close to zero. This is a result of the implemented

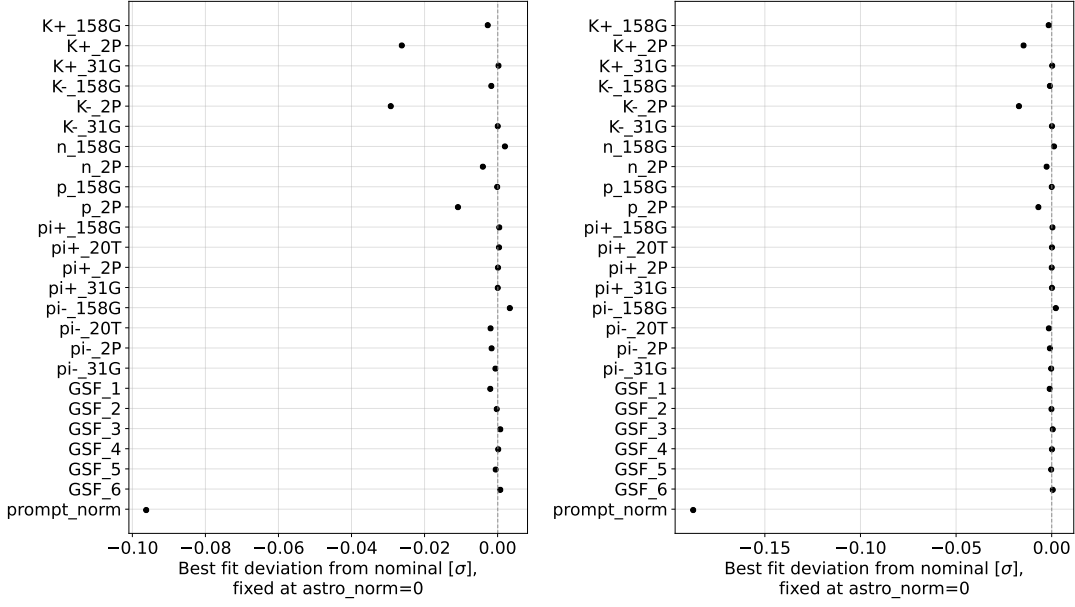


Figure 21: Best fit deviation from nominal for each DAEMONFLUX parameter

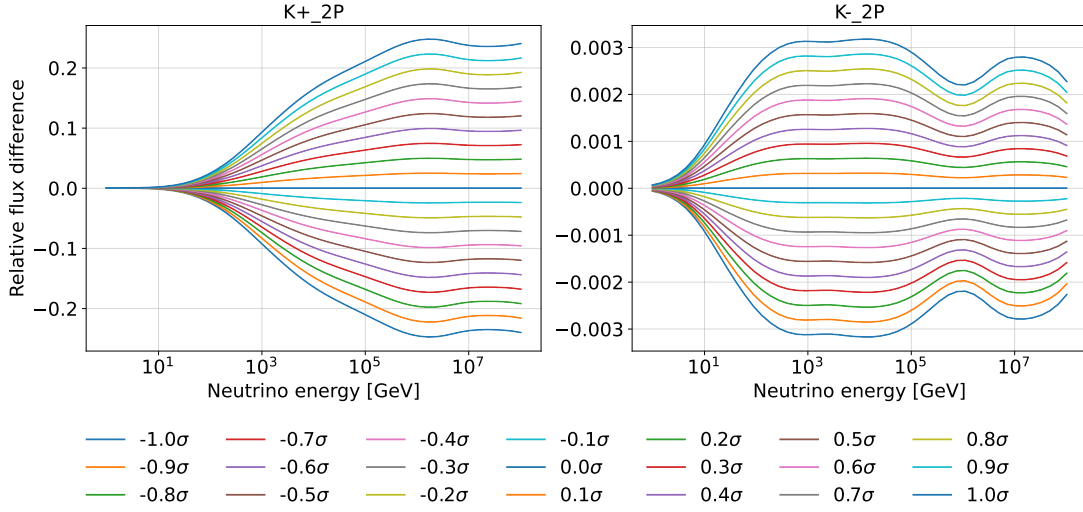


Figure 22: Calculated flux at a fixed angle, with only one of the 24 DAEMONFLUX parameters fixed to a certain value, each curve depicting the fix to a different value in units of the parameter's standard deviation

Gaussian priors on these parameters and is also the case for the same plot, but for case A, which can be seen in Figure 21b.

5.4 Data-MC-Agreement

Finally, the flux models were checked against real KM3NeT data. This dataset was a burn sample, in this case, only 10% of what was actually measured, was used, so that

no bias would impact the analysis.

For the energy as well as the zenith angle, comparisons of the injected MC values with this data, can be seen in Figure 23: one curve with MCEq, and one with DAEMONFLUX. Similar plots were also created using fitted MC data, shown in Figure 24.

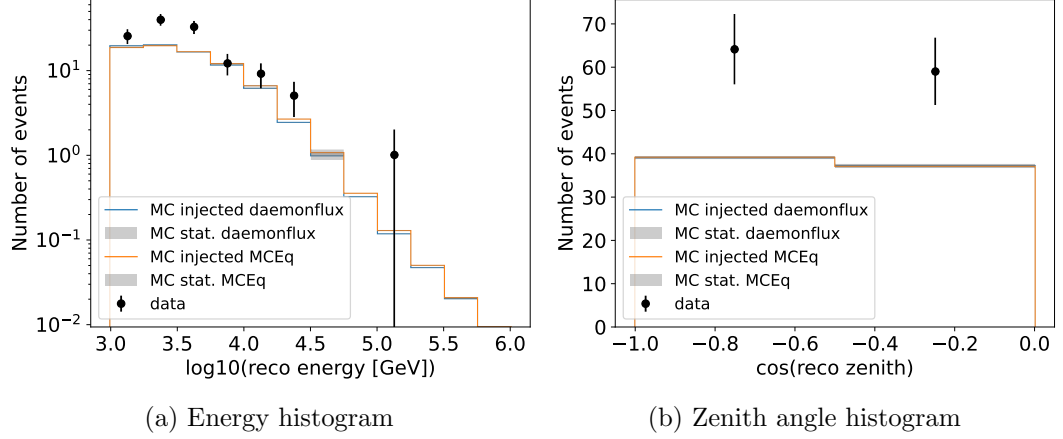


Figure 23: Histograms comparing the injected MC to the real data, using both models, DAEMONFLUX and MCEq

It can be seen that the the graphs using fitted MC values match the data better than

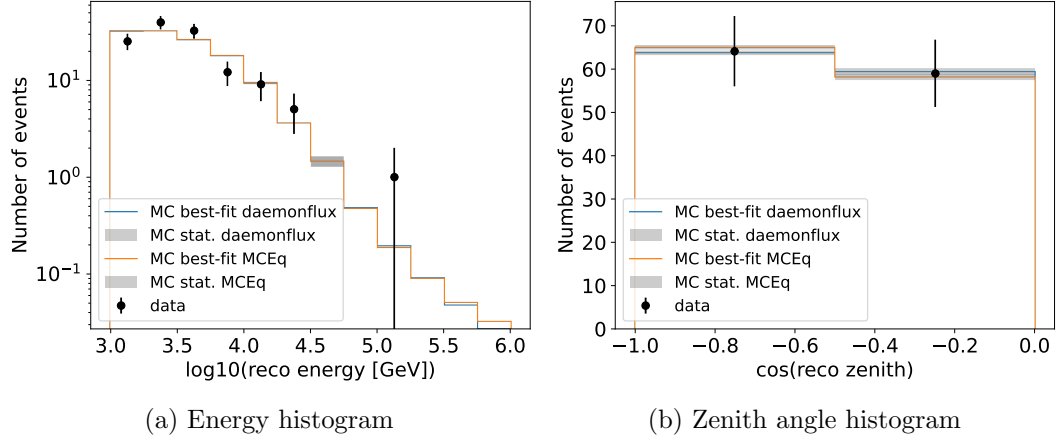


Figure 24: Histograms comparing the fitted MC to the real data, using both models, DAEMONFLUX and MCEq

the ones using injected values. Also, in both cases, DAEMONFLUX and MCEq are very similar.

Additionally, pull plots were created. The pull was calculated using the following Equation 21, where D refers to the real data, M to the MC prediction and σ_i to their respective uncertainties:

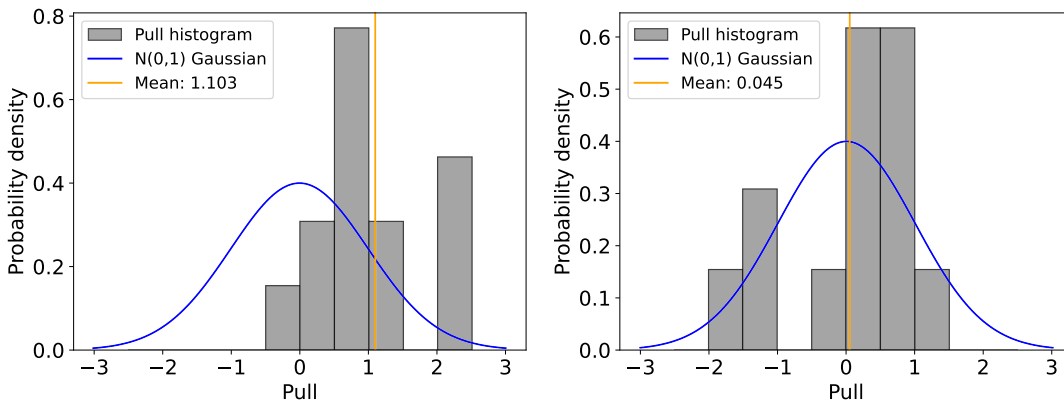
$$\text{pull} = \frac{D - M}{\sqrt{\sigma_D^2 + \sigma_M^2}} \quad (21)$$

So the pull refers to the difference of the real data and the MC prediction in units of the standard deviation σ .

The used uncertainties are Poisson uncertainties, meaning the square root of the data itself.

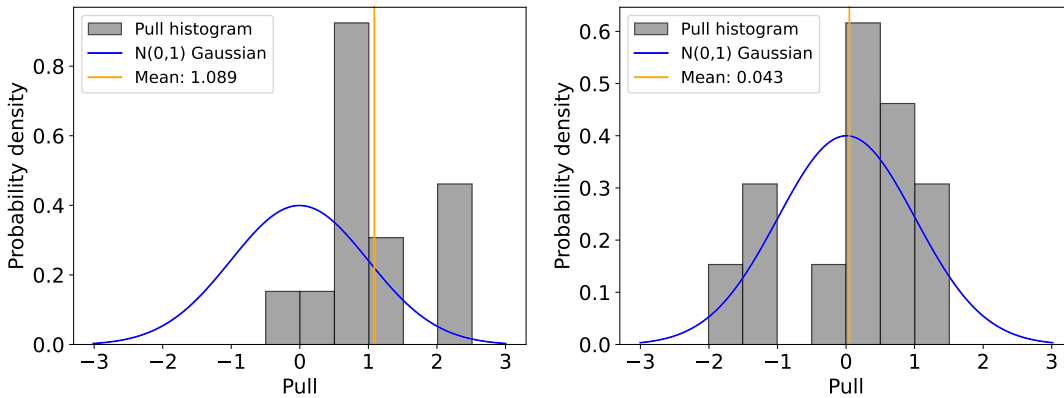
The plots in Figure 25 show how this difference is spread across all bins using the DAEMONFLUX model. The plots using MCEq can be seen in Figure 26. In case the model and its uncertainties are ideal, the plot should follow a Gaussian with a mean of 0.0 and a standard deviation of 1.0. This ideal curve is shown in blue and referred to as 'N(0,1) Gaussian' in the plots. In case the mean of the pull is positive, MC underestimates the data, in case it is negative, the data is overestimated. The pull means are shown in orange in the plots.

One can see that for both MCEq and DAEMONFLUX with injected values, the mean



(a) DAEMONFLUX pull plot using injected MC values (b) DAEMONFLUX pull plot using fitted MC values

Figure 25: Pull histogram plots, each using DAEMONFLUX, also depicting the ideal Gaussian curve as well as the mean



(a) MCEq pull plot using injected MC values (b) MCEq pull plot using fitted MC values

Figure 26: Pull histogram plots, each using MCEq, also depicting the ideal Gaussian curve as well as the mean

is approximately 1.1σ , meaning the data was underestimated. However, with fitted values, the mean is much closer to zero, with a value of approximately 0.04σ . This matches the results from the histograms, which show that in the plots using fitted values instead of injected ones, the MC prediction matches much better with the real data. This shows that the fits do well at adjusting the model prediction to the KM3NeT data, resulting in the matching of this data and the model curves in the histograms, and the pull mean being very close to zero for the plots using the fitted MC values. Additionally, the plots further prove that DAEMONFLUX and MCEq provide consistently similar results.

6 Conclusion

In this thesis, the atmospheric neutrino flux model DAEMONFLUX is first implemented and then compared to a previously used model, MCEq.

This comparison was done by applying both models to certain flux analysis methods. The first one discussed was plotting flux density histograms over both the reconstructed energy as well as the zenith angle. In these histograms, the resulting curves for MCEq and DAEMONFLUX mostly overlap, firstly indicating a high similarity.

Then, 1D and 2D likelihood scans were performed. The 1D scans included an additional model, the Gaisser model. In the 1D astro norm scans, the DAEMONFLUX scan was narrower than the MCEq scan, indicating a stronger constraint of the parameters.

A 2D scan comparing the two models showed similar results and further confirmed their similarity.

Furthermore, a model confusion check, meaning the injecting and fitting of different models, showed a generally higher discovery sensitivity when fitting with DAEMONFLUX. For the cases in which different models were fitted, a non-trivial bias could be observed, while the cases using the same model both times showed a bias of 0.0, due to the Asimov test.

Finally, the two models were checked against data from KM3NeT/ARCA and histograms comparing the models to this data were created. In one case using injected, and one using fitted MC values. The plots show that generally, the histograms using fitted MC fit better to the real data. Additionally, the two models provide very similar results again, with all histogram curves mostly overlapping and both models sufficiently describing the burn sample.

In summary, the analysis DAEMONFLUX was applied to, shows, that the implementation of the model worked, due to the results strongly resembling those of MCEq in all approaches.

Using the current statistics from the ARCA21 analysis, MCEq and DAEMONFLUX cannot be distinguished, as can be derived from the bias, histograms and data checks. This similarity indicates that DAEMONFLUX is a suitable model candidate for further atmospheric neutrino flux studies and should be used in future research with KM3NeT/ARCA. Using DAEMONFLUX would be beneficial due to its advanced concept of parameter correlation.

Acronyms

AGN Active Galactic Nuclei.

ARCA Astroparticle Research with Cosmics in the Abyss.

DAEMONFLUX DAta-drivEn MuOn-calibrated atmospheric Neutrino Flux.

DDM Data-Driven hadronic interaction Model.

DOM Digital Optical Module.

DOMs Digital Optical Modules.

DU Detection Unit.

DUs Detection Units.

FPGA Field Programmable Gate Array.

GRBs Gamma Ray Bursts.

GSF Global Spline Fit.

KATRIN Karlsruhe Tritium Neutrino Experiment.

KM3NeT Cubic Kilometre Neutrino Telescope.

MC Monte Carlo.

MCEq Matrix Cascade Equations.

NaN Not a Number.

NNMFit NewNuMuFit.

ORCA Oscillation Research with Cosmics in the Abyss.

PCA Principal Component Analysis.

PMT Photo Multiplier Tube.

PMTs Photo Multiplier Tubes.

PWNe Pulsar Wind Nebulae.

pyFF pyForwardFolding.

RNO-G Radio Neutrino Observatory Greenland.

SBGs Starburst Galaxies.

A Appendix A

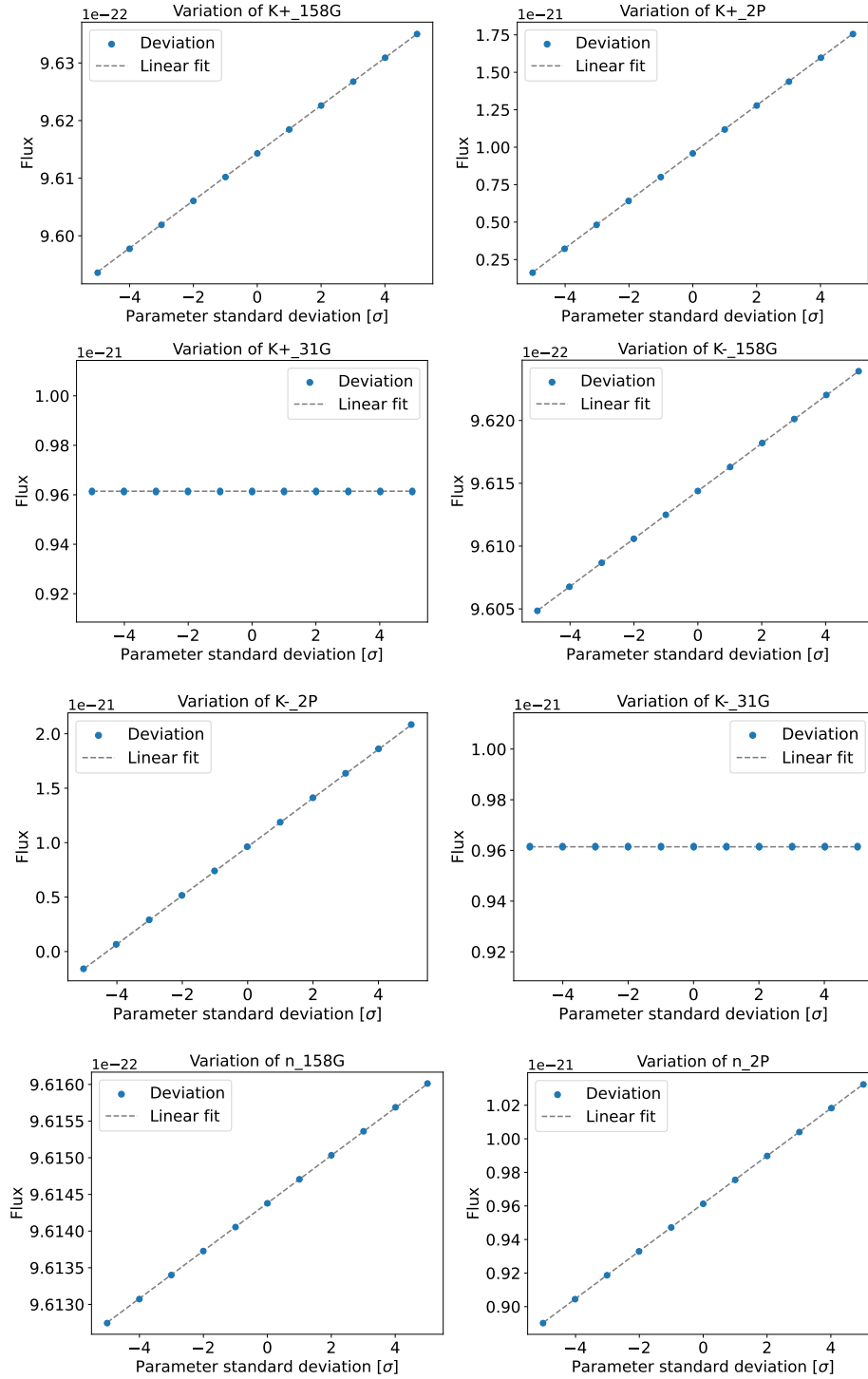


Figure 27: All linear graphs used to calculate the DAEMONFLUX GradientReweights (plots 1-8)

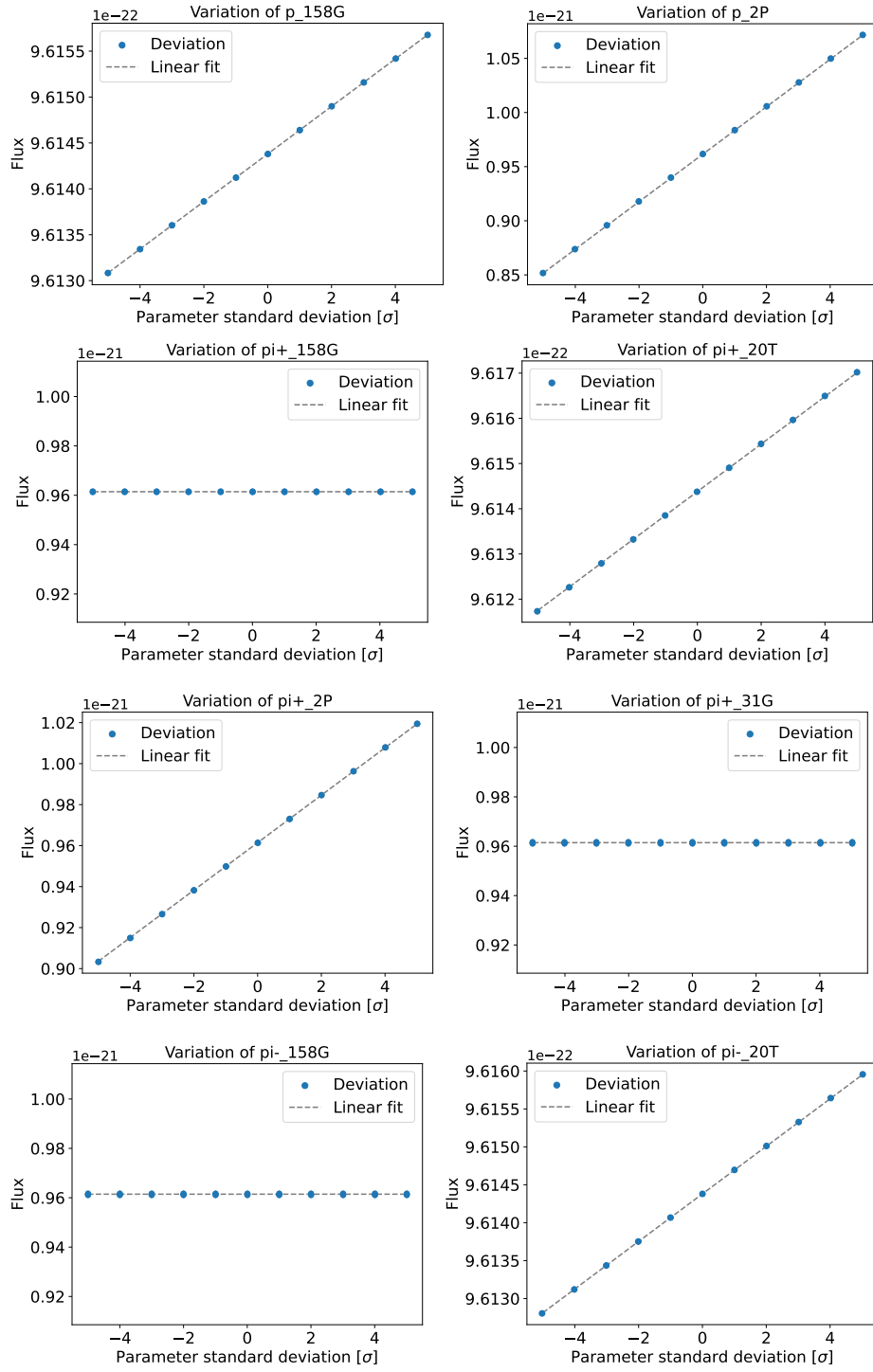


Figure 27: All linear graphs used to calculate the DAEMONFLUX GradientReweights (plots 9-16)

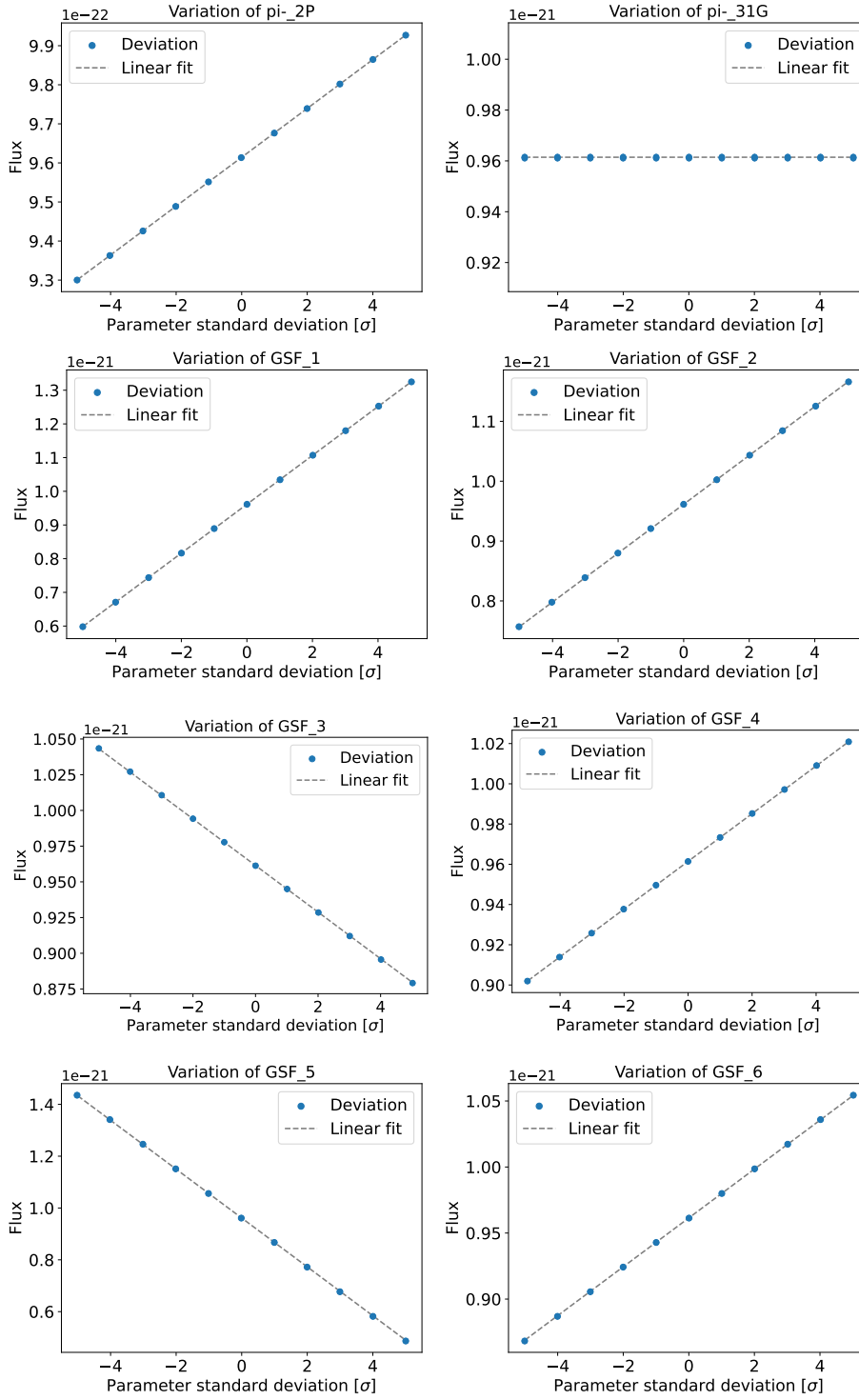


Figure 27: All linear graphs used to calculate the DAEMONFLUX GradientReweights (plots 17-24)

B Appendix B

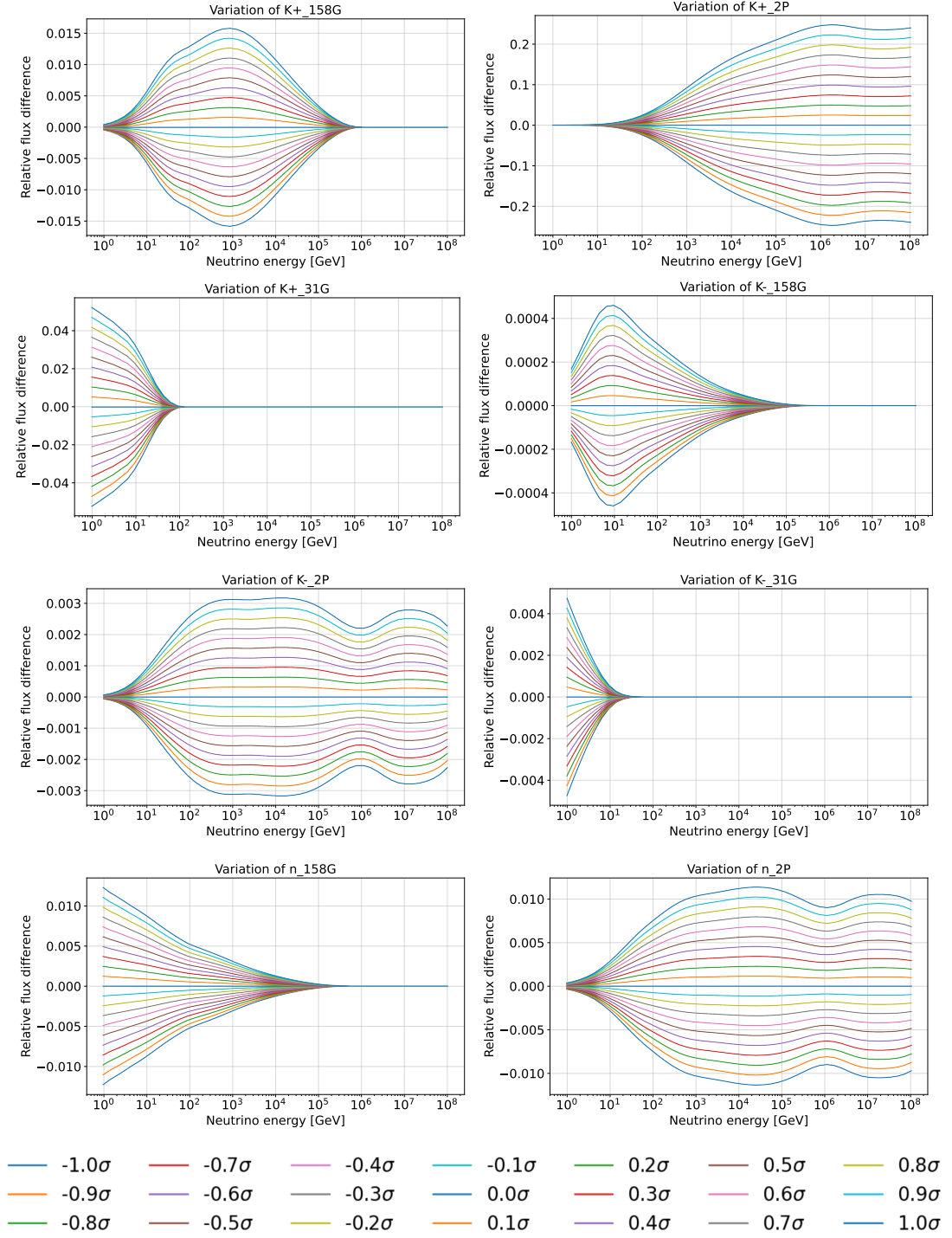


Figure 28: All DAEMONFLUX parameter variation plots used to determine at which energies each parameter takes effect (plots 1-8)

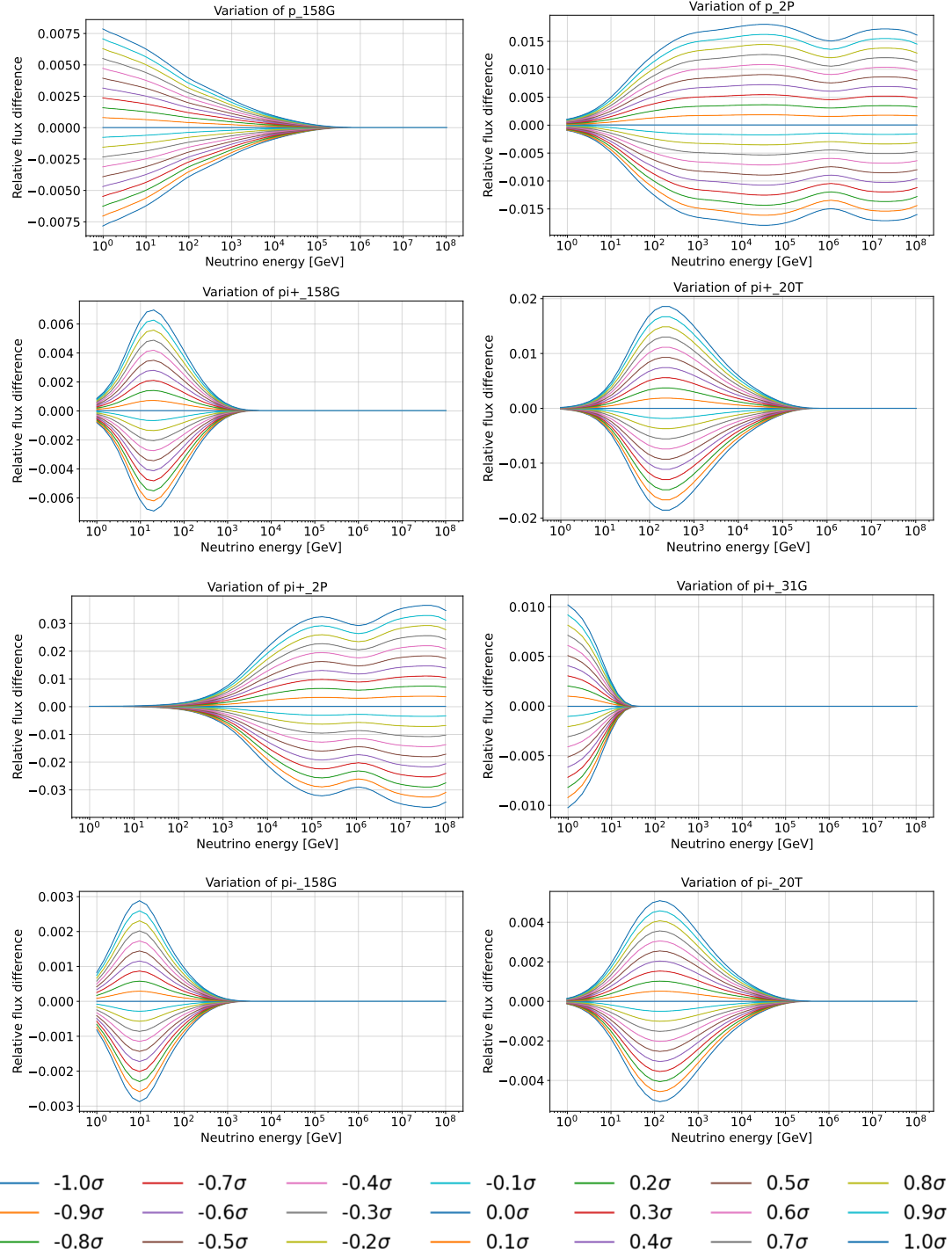


Figure 28: All DAEMONFLUX parameter variation plots used to determine at which energies each parameter takes effect (plots 9-16)

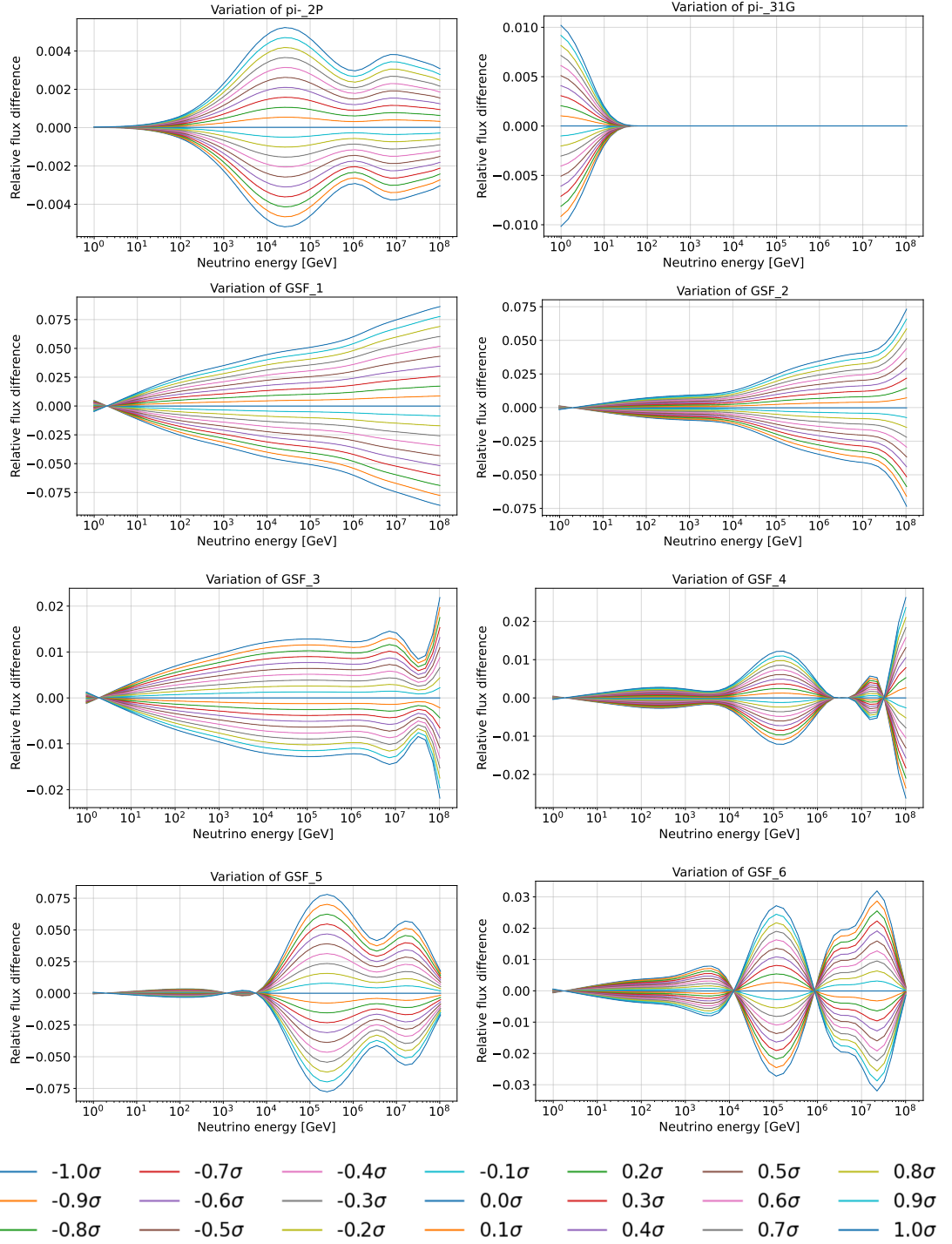


Figure 28: All DAEMONFLUX parameter variation plots used to determine at which energies each parameter takes effect (plots 17-24)

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Declaration of Originality

I, Lina Seitz, student registration number: 23345451, hereby confirm that I completed the submitted work independently and without the unauthorized assistance of third parties and without the use of undisclosed and, in particular, unauthorized aids. This work has not been previously submitted in its current form or in a similar form to any other examination authorities and has not been accepted as part of an examination by any other examination authority.

Where the wording has been taken from other people's work or ideas, this has been properly acknowledged and referenced. This also applies to drawings, sketches, diagrams and sources from the Internet.

In particular, I am aware that the use of artificial intelligence is forbidden unless its use as an aid has been expressly permitted by the examiner. This applies in particular to chatbots (especially ChatGPT) and such programs in general that can complete the tasks of the examination or parts thereof on my behalf.

Any infringements of the above rules constitute fraud or attempted fraud and shall lead to the examination being graded "fail" ("nicht bestanden").

Place, Date

Signature